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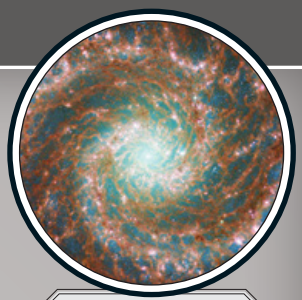

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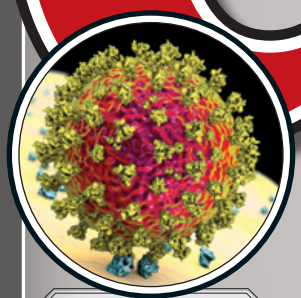

THE LEGACY OF **COVID-19**

HOW **MISINFORMATION** IS MISLEADING SOCIETY

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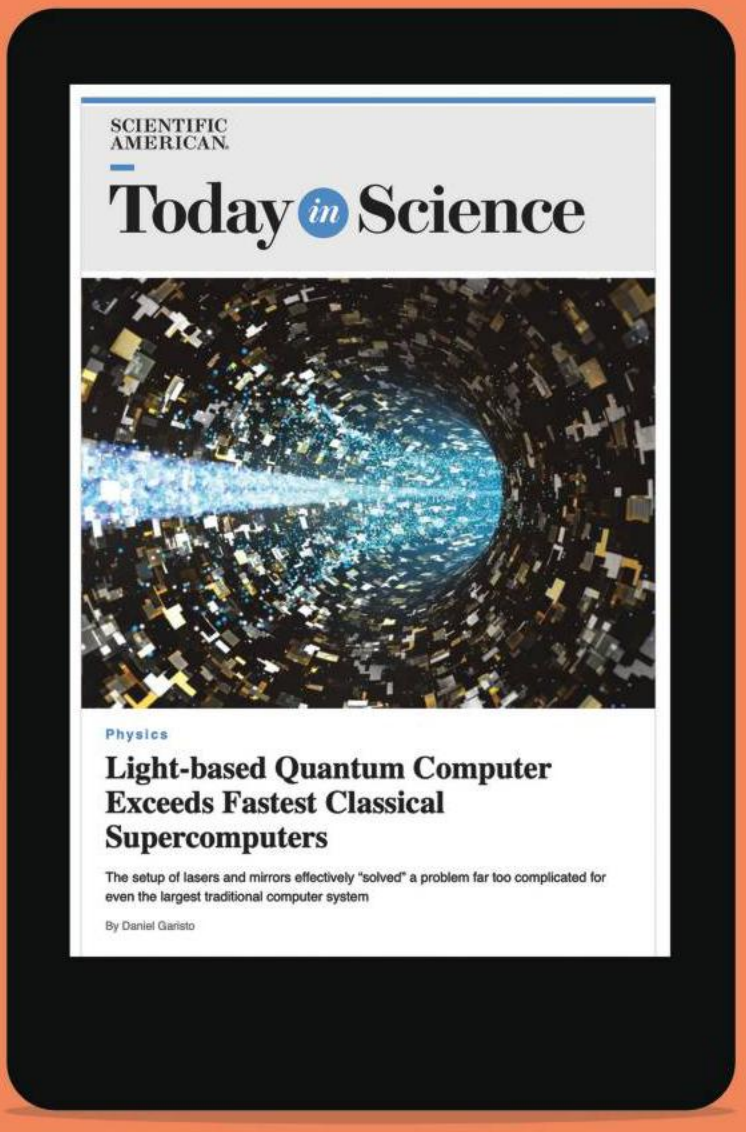
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Today in Science
Physics
Light-based Quantum Computer Exceeds Fastest Classical Supercomputers
The setup of lasers and mirrors effectively "solved" a problem far too complicated for even the largest traditional computer system
By Daniel Garisto

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FROM THE EDITOR

A Year of Wonder, Awe and Discovery

Last July, NASA revealed the first images sent back from its highly anticipated new space telescope. Gorgeous photographs of swirling galaxies, fiery nebulas and newborn stars stunned the world. As one of the lead scientists working with the scope's near-infrared camera said, "We are now seeing that the science returns are probably going to be even greater than we had dared to hope." The luminous set of pictures reminds us that despite an ongoing and devastating global pandemic, research and discovery in all disciplines have carried on. The past year saw inspiring revelations not only in space and physics but also in biology, ecology, technology, and beyond. This collection presents some of *Scientific American*'s best articles, as chosen by our editors, related to the most important events of 2022.

Schoolchildren hold placards and chant as they attend a climate change protest organized by Youth Strike 4 Climate, opposite the Houses of Parliament in London.

To start, mind and mental health researchers have identified the underpinnings of two fascinating, complex psychological phenomena: the injurious experience of gaslighting (*page 4*) and children's inheritance of trauma from their parents (*page 10*). A new analysis speculates that the troubled U.S. health-care system is responsible for an unnecessarily high death toll from COVID (*page 18*).

Back to one of the most significant achievements of the year: the launch of the James Webb Space Telescope. After mere months of operation, JWST is sending images that are already turning physics inside out (*page 42*) and, astronomers hope, might foster new clarity in one of the biggest debates in cosmology (*page 60*). A planet-size network of powerful telescopes brought the behemoth black hole at the center of the Milky Way into focus in September, and the result is astounding (*page 36*).

Many countries experienced record-breaking heat waves in 2022, and temperatures will not be cooling off any summer soon (*page 66*). Warming global temperatures are fracturing ice shelves and melting glaciers in Antarctica and elsewhere (*page 76*). Intriguing new findings illustrate how birds use Earth's magnetic field to migrate thousands of miles every year, a long-standing mystery in biology (*page 70*). And another poorly understood wonder was illuminated by science: the potential cause of ghostly glowing ocean water, records of which go back more than 150 years (*page 86*).

Science elucidates nearly every societal issue we face. Sociologist Amy Cooter writes about the psychology of some radicalized U.S. militia groups whose actions are becoming more violent (*page 116*). An in-depth investigation by reporter Katie Worth reveals the ways that oil industry representatives influence what children learn in school about climate change (*page 94*). And Russian authorities use digital tools to repress truthful information about their country's invasion of Ukraine (*page 110*).

As evinced by harmful laws that hinder health care for transgender young people (*page 128*), the revoking of a federal right to abortion (*page 16*), and the undoing of protective gun laws (*page 124*), a troubling disdain for scientific evidence and reason plagued many policy developments in 2022 (*page 130*). Scientific experts must advocate science and reason as the foundation of public policy. And may this collection demonstrate that science can also offer returns beyond policy and a sound and just society—in pure wonder and awe.

Andrea Gawrylewski
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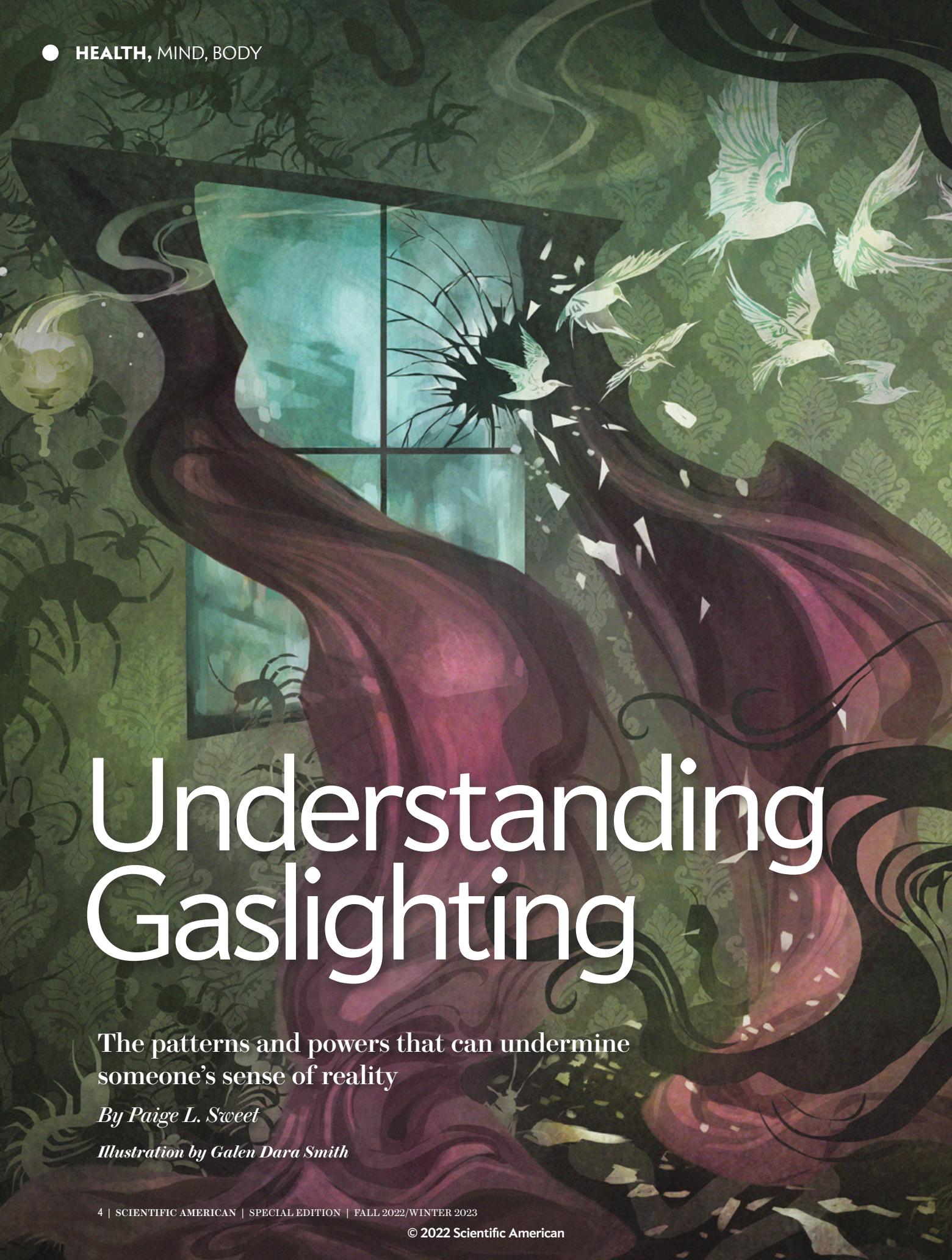

Understanding Gaslighting

The patterns and powers that can undermine someone's sense of reality

By Paige L. Sweet

Illustration by Galen Dara Smith

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DURING HER 12-YEAR MARRIAGE, "CHANDRA" SAYS, HER HUSBAND ROUTINELY cheated and then told her she was "crazy," "jealous" and "paranoid" when she produced evidence of his affairs. He often used the word "irrational," historically a term used to demean women. Chandra worked, went to school and provided all of the care for their children, yet her husband convinced her that she needed him. He would, for instance, intentionally delay paying bills and then blame her when the lights were shut off—a strategy of financial control that made her feel dependent on him. During an hour-long Zoom interview as part of my research, Chandra repeatedly described her ex-husband as a gaslighter.

After ending the call with Chandra (a pseudonym to protect her privacy and safety), I jotted down notes: confusion, unequal caregiving responsibilities, shame, credibility loss, gender-based insults, verbal abuse. Her experiences are typical of the stories I've collected about gaslighting over the past few years. Over time the way Chandra's ex-husband called her "crazy" and accused her of "overreacting" made her doubt herself as a reliable witness to her own experiences.

But this effect was not produced in a vacuum. Chandra was socially isolated from her friends and family. She was experiencing financial stress as well as a lack of support around balancing child care with her jobs. These vulnerabilities made her less able to resist her husband's manipulations, and she became psychologically exhausted and entrapped. Chandra questioned her perception of reality, her memory and her ability to interpret events. She wondered if she *was* crazy.

Gaslighting is broadly defined as a type of psychological abuse that makes someone seem or feel "crazy." It resembles other forms of psychological abuse and can be thought of as a subset of this larger category. We know that psychological abuse, and "crazy making" in particular, is a core feature of domestic, or intimate partner, violence. It functions in part by convincing victims that what they are experiencing is not real or important and then blames them for their experience.

The result is what sociologist Kathleen Ferraro has called the "surreality" of abusive relationships or what scholar and activist Beth E. Richie refers to as a "hostile social environment." The word itself comes from a 1930s play called *Gas Light* that was turned into a 1944 film starring Ingrid Bergman. In it, the protagonist's husband secretly dims and brightens the gas-powered indoor lights and insists she is imagining it, making her believe she is insane.

Over the past decade the term has become astronomically popular. Partly this is a result of the success of the #MeToo movement, which illuminated how victims of sexual violence and harassment are systemically doubted and discredited when they go public. Commentators have also used it to describe the mind-bending denials of reality coming out of the White House during the Trump presidency. The term "gaslighting" has exploded online among Twitter, Instagram and TikTok users interested in mental health, as well as among political and culture writers and popular psychologists.

But even though everyone seems to be talking about gaslighting, this type of abuse is just starting to be studied using systematic social scientific data. Although we tend to think of gaslighting as a problem between two people in a relationship, it also unfolds as part of an unequal social context. Gaslighting feeds off social vulnerabilities and stereotypes. It entrenches existing power imbalances while fostering new ones. The term is also increasingly used to describe structural racism, sexism, homophobia and ableism. Scholars and activists have used the term "racelighting," for instance, to name racial microaggressions that undermine the experiences of people of color and the ideologies that cover up these behaviors; a 2021 policy report described race-based gaslighting as "institutionalized in the social fabric."

Social theorists and writers from marginalized backgrounds have long insisted that social power works by trying to convince us that everything is normal while the conditions surrounding us are discriminatory and oppressive. As psychiatrist Ann Crawford-Roberts and her colleagues argued in 2020, watching George Floyd's murder by a police officer and then being told his death was the result of preexisting medical conditions is "structural gaslighting." Our task as sociologists is to follow the elusive, topsy-turvy ways in which social domination operates. We must follow what sociologist Avery Gordon calls the "spells of power" and the way patterns of noncredibility are established. By taking gaslighting seriously, we can learn about the relation

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between macro-level inequalities and the "micro" forms of silencing and disempowerment that people experience in their everyday lives.

DANGEROUS RELATIONSHIPS

AS A SOCIOLOGIST, I'm interested in the social conditions and intimate dynamics that allow gaslighting to occur. In 2021 I set out to use in-depth qualitative research to figure out what makes gaslighting such an immiserating force. To find interview participants, I posted ads on social media defining gaslighting loosely as someone trying to make you "seem or feel crazy." This recruitment strategy allowed anyone who defined their experiences as "gaslighting" to participate, no matter where or how they experienced it.

After conducting 122 interviews over six months and analyzing the patterns that make up this form of abuse, I became most intrigued by the social contexts where we find gaslighting, and its relation to inequalities around gender, sexuality, class, ability and race. Unsurprisingly, gaslighting does not involve just one of these axes of identity—rather people experience gaslighting intersectionally, meaning that factors such as age, race, gender and sexuality all matter for the way people's realities are distorted, questioned or denied.

Based on my sample, there appear to be four central relationships or contexts in which gaslighting typically occurs: domestic violence; intimate partners who are not otherwise abusive; parents and other family members; and institutional gaslighting, primarily in the workplace. These forms of gaslighting rely on different dynamics—for example, domestic violence situations often include verbal abuse, whereas workplace gaslighting often has to do with racial discrimination. But they all involve power imbalances. This matters because it teaches us to ask different questions. Not, "Why did this person do that and what should the victim do in response?" But rather, "Who is establishing power and authority and how?" What follows are examples of these four contexts.

The experiences of "Selah" typify the domestic violence type of gaslighting. Selah's ex-husband questioned her sanity for years, telling her she needed medication and that her family thought she was "unstable." He once called a crisis mental health team to the house, claiming Selah was suicidal and couldn't be left alone. After Selah left him and got her own apartment, her husband broke in while she was at work and made himself comfortable. When Selah arrived home, he pretended that nothing was amiss and asked what they were having for dinner. He distorted Selah's reality (she had left him) by insisting on his own reality (they were still together). He peppered subtle threats throughout their conversation and wouldn't let her leave the house to get groceries.

This was part of a years-long pattern: Selah's husband stalked and harassed her each time she tried to leave, until eventually she fled in secret to a domestic violence shelter halfway across the country. This abuse had a sinister quality that made it difficult for Selah to describe what was happening. After all, what's wrong with your husband coming over and asking what's for dinner? As Selah explained, "They live in an alternate reality. And they want you to live there with them."

Around 30 percent of the people I interviewed identified their parents as their primary gaslighters. "Audrey" feels that her mother doesn't take her mental health problems seriously, insisting that Audrey's depression and anxiety are not "real," that she's just being "lazy," a "drama queen" and "overreacting." Audrey has been hospitalized for her mental illness, has attempted suicide, and receives government assistance because her symptoms make her unable to work. Still, Audrey worries that no one will believe her symptoms are real. Audrey told me: "Maybe I *am* a loser. Maybe I have really poor character. Maybe I'm just whiny."

Because of these fears, Audrey delays treatment and minimizes her symptoms. Her experiences exemplify a type of gaslighting that tends to start in childhood and persist over long periods. This gaslighting often involves a parent denying a child's experiences in a way that exacerbates isolation and self-doubt. Here Audrey's mother controls resources (housing, finances) and wields a significant amount of emotional power over Audrey, a kind of authority rooted in the parent-child relationship.

> Although we tend to think of gaslighting as a problem between two people in a relationship, it also unfolds as part of an unequal social context.

When "Maya" tried to get her boss to stop telling sexually inappropriate jokes at work, he accused her of "overreacting." Things got worse, and when she put in her two weeks' notice, she was asked to leave and not come back. After she filed for unemployment and claimed in the request for unemployment compensation that it was a toxic work environment, her boss—a lawyer—contested her claim with a 500-page document asserting that she had laughed at his jokes, so how could they be offensive? In other words: she must be making it up. He claimed that Maya had gone "bar hopping" during the pandemic, endangering the safety of her co-workers, even though Maya had been pushing for masking at work. "Everything that I was doing to try and keep myself safe, he would twist it around … to appear that I was doing something nefarious or out of malevolence." As the only nonwhite person in her office, Maya felt that he used stereotypes of people of color as

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aggressive to make her out to be a danger to the office.

"Alex," whose fiancé gaslit her while they were in college, was not fearful of her partner. Unlike the other examples given here, their relationship appeared to be equal. But Alex was constantly made to blame herself for her partner's actions, and a power imbalance quickly emerged. Alex's partner would cheat on her and then deny it was happening. When Alex questioned her, she would say that Alex was "jealous" and "possessive" and ask why Alex didn't value friends and "chosen family" as much as she claimed to. Alex felt confused and guilty; she stopped eating and sleeping. She started a journal in which she wrote down things her partner said to keep a record, fearful that her partner would undermine her memories.

Alex described herself as "dazed" and "numb" during the relationship. She explained that it was hard to identify this experience as "gaslighting" because there was no clear gender-based power differential between her and her same-sex partner. Alex's experiences typify gaslighting in relationships that are not otherwise abusive, such that the manipulations were subtle and indirect but nonetheless made Alex doubt her ability to interpret reality. Unlike in Selah's case, verbal abuse, extreme control, threats and physical intimidation were not part of the equation. Instead Alex's partner gained power in the relationship by using Alex's own values against her, insisting Alex was being "jealous," a trait they both believed was toxic. She argued that Alex should be disappointed in herself.

Shame is central to gaslighting because it keeps victims trapped in the exhausting cycle of defending themselves against assaults on their integrity.

What ties these stories together? Although strategies of abuse vary among cases, they all depend on the mobilization (or creation) of a power imbalance against the victim. The material effects of gaslighting may be more extreme in some cases (Selah received threats to her life; Maya had to leave a job in the middle of a pandemic), but what remains consistent is that controlling resources and narratives is key to how power imbalances are established and reproduced.

PATTERNS OF MANIPULATION

OUR FIRST TASK, then, is to reframe the way we think sociologically about abuse: gaslighting, like other forms of intimate violence, is not an incident but a process. Through my research, I've found that gaslighting typically unfolds as denial or distortion, isolation, shame, and attacks on credibility. The basic pattern is to deny or occlude, then flip the script. This pattern holds whether the perpetrator of gaslighting is a parent, friend, partner, mentor or boss.

When gaslighting is severe and affects victims' lives in lasting ways, this pattern occurs in a context of isolation and as part of a power imbalance between the gaslighter and the victim. That imbalance may be the result of widespread social inequalities—for example, between male and female partners or between a white boss and a Black employee. Or it may be naturalized in the family, such as the age and authority differential between parent and child. This is what understanding gaslighting with sociological tools allows us to see: mental manipulation typically relies on existing social patterns of domination.

The classic film example of gaslighting suggests that an abuser intentionally distorts his partner's sense of reality. My research shows that gaslighting may be unintentional—for example, Audrey doesn't think her mother gaslights her on purpose. But it can also involve denial of another's reality. When Selah's ex showed up at her house and pretended everything was normal, he was denying the reality that she had left him. Alex and Chandra's ex-partners both denied clear evidence of affairs and then disoriented Alex and Chandra with accusations of jealousy. Maya's boss denied her experiences of harm in the workplace, distorting her responses to his jokes. Denying someone's reality and distorting interpretations of past events are key to all forms of gaslighting.

Disorientation and denial are most effective if they take place in a context of isolation. For example, although Alex's partner did not "isolate" her in the extreme way that many abusers do, the gaslighting occurred while she and her partner were out of the country, where Alex felt alone and out of sorts.

"Imani," a domestic violence victim, explained that she became isolated because her abuser turned her against her own family. "He would make me think they're not good for me.... I wouldn't go down there [to visit family] anymore. [He would say,] 'Why would you want to be around somebody that wasn't there for you?'" Imani started to believe that her partner was the only one who loved her, that the rest of the world was against her. She no longer wanted to socialize; she didn't even want to go outside. Imani's experiences show how gaslighting turns inward. She came to believe she wanted the isolation.

This is important because isolation prevents victims from hearing a counternarrative to what's happening in the relationship. For example, as part of institutional gaslighting, Maya's boss accused her of unethical work practices and forced co-workers to surveil her communications, leaving her alienated and her colleagues suspicious. Domestic violence and institutional gaslighting tend to involve the most extreme forms of isolation. Isolation, as one of my interviewees put it, is the "breeding ground" for gaslighting.

Gaslighting also works by instilling shame, which

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makes victims feel that the abuse is their fault. "Summer" explained that her partner likes to provoke her into fights. He needles her with insults and stories of his relationships with other women, whom he says are better than her at cooking, at sex, at being a mom. He waits until she starts crying and yelling. "And he stood there, and he goes, 'You're acting really crazy right now, and I do not understand why,'" Summer recalled. "And I was like, oh, my gosh, it's finally happening to me … I'm tearing things off the wall … I just could not take it anymore…. And then [he had this] look, pitiful, on his face. He's like, 'I was just trying to have a conversation with you.'"

Here Summer's boyfriend, who has strangled Summer and threatened her with guns, flipped the situation to make her out to be unstable and violent. He then used her intense shame about "going psycho" to threaten that he would tell others about how she acted. Shame is central to gaslighting because it keeps victims trapped in the exhausting cycle of defending themselves against assaults on their integrity.

Shame also weakens a victim's credibility with themselves and others. The result is what feminist philosophers call "testimonial injustice," wherein prejudice causes people to withhold credibility from someone's narrative. Summer's abuser told his family that she is the one who beats him and lies about it. This strategy of "credibility slashing" is effective even though he is on probation for domestic violence.

Attacks on victims' credibility often work by appealing to community values, as when "Elyse's" ex-husband told friends and family that she was acting "ungodly" and out of character after filing for divorce. Making a victim seem unstable in trusted social networks exacerbates isolation.

Victims experience attacks on their credibility across types of gaslighting, although the form of those credibility attacks is specific to the institutional and social context in which gaslighting occurs. These attacks matter for legal proceedings such as divorce (for Elyse) and unemployment filing (for Maya). Attacks on credibility also diminish victims' ability to trust themselves, to know that what they are experiencing is real. Victims often come to feel that no one will believe them, making them doubt themselves as reliable witnesses.

TAKING GASLIGHTING SERIOUSLY

DESPITE THE CONSEQUENCES of this abuse, "gaslighting" has the makings of a flash-in-the-pan buzzword. The term has plenty of skeptics, especially among academics and commentators who argue that it lacks clarity and is overused. "Gaslighting" is indeed used in fast and loose ways in popular culture, without the rigor of social scientific research to back it up. It's often wrapped up in self-help culture, which can perpetuate messages that focus on individuals' actions and reinforce victim blaming. Sometimes it's conflated with simple lying or with other kinds of emotional abuse such as humiliation.

I agree with many of these criticisms. But mostly I'm relieved that we now have a language to talk about psychological abuse and its links to oppressive structures such as racism and ableism. Learning the term "gaslighting" gave Chandra, a 50-year-old Black woman, a container for identifying real patterns of abuse and discrimination. She's in a happier marriage now, but her happiness has been hard won: By leaving her ex-husband, seeking out higher-paying jobs, and working with counselors to identify her ex's abusive behaviors, she was able to regain her autonomy. If people such as Chandra are using "gaslighting" to make sense of confusing and harmful experiences, I think we have a net positive here. After all, there's nothing precious about a made-up word from a movie—so why not use it to name confusing forms of injustice and to argue for more equal social relationships?

Undeniably, gaslighting is a harmful type of psychological abuse that preys on people's social vulnerabilities. High rates of psychological abuse reported more generally suggest that researchers should pay closer attention to gaslighting and its lasting effects on victims' lives, regardless of whether physical violence is also present. One of the clearest patterns to emerge from my research is that the effects of gaslighting are worse for people who lack social networks and structural protections.

Some of those supports are things policy makers could choose to provide. For example, when people have access to a living wage, child care and safe housing, they are less dependent on bad jobs and abusive partners. Would Chandra have stayed with her gaslighting husband for 12 years if she had access to money and child care? Would Audrey's mother's gaslighting be so effective if Audrey's disability benefits paid enough that she could live on her own? People who experience gaslighting around their material vulnerabilities are particularly at risk of staying in bad relationships longer.

Robust social networks of friends, family and neighbors also matter. Generally, the people I interviewed who were able to leave gaslighting relationships quickly had people they could rely on to validate their realities and give them positive counter-narratives about their self-worth. Gaslighting is harmful not only because it draws from and exacerbates social inequalities but because it becomes internalized in a context of isolation, making one question one's sense of self. Coming to doubt oneself as a reliable interpreter of the world does significant damage. But context matters. If social networks and community support are protective, we can rely on one another to prevent or reverse the worst effects of gaslighting. SA

Paige L. Sweet is an assistant professor of sociology at the University of Michigan and author of *The Politics of Surviving* (University of California Press, 2021).

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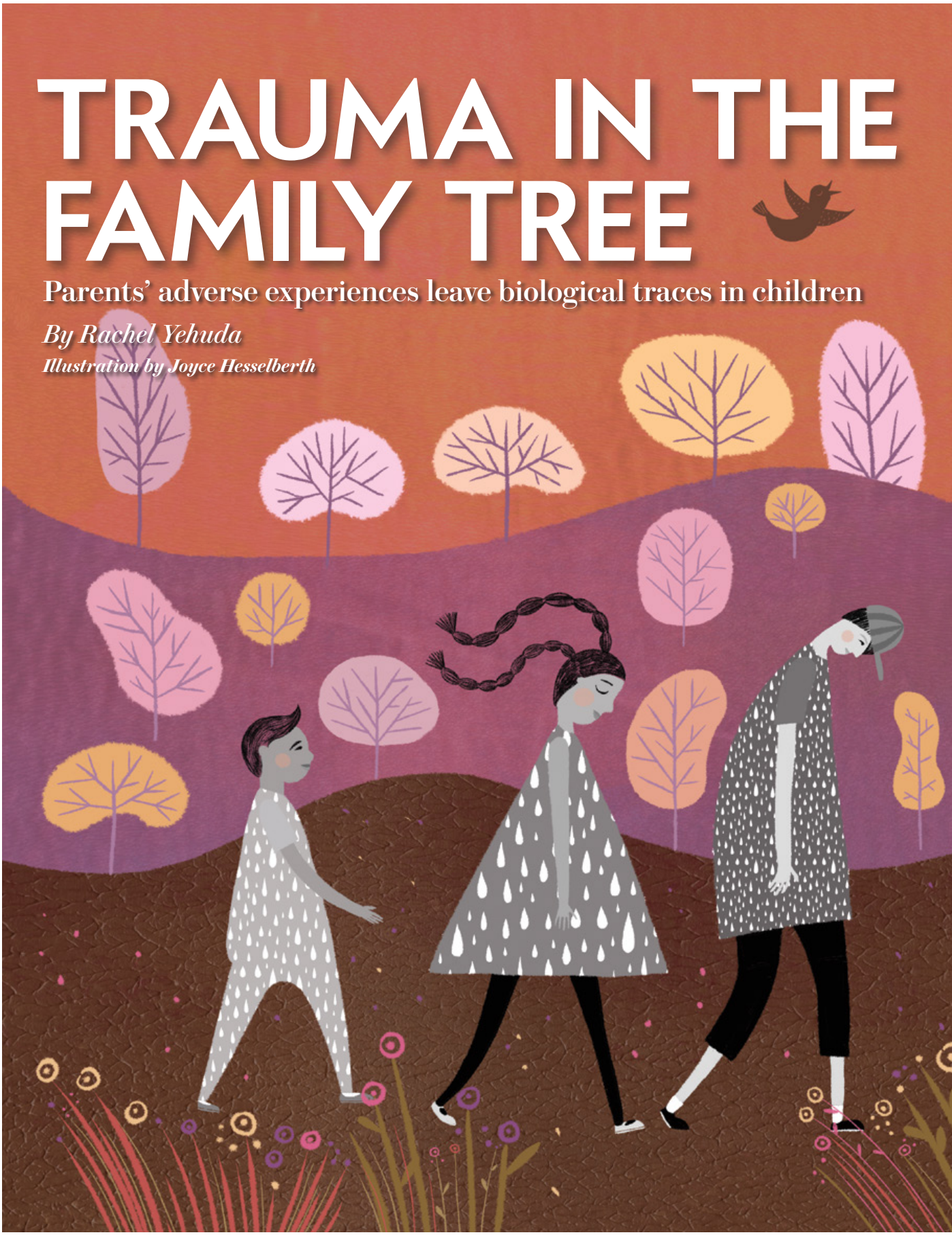
TRAUMA IN THE FAMILY TREE

Parents' adverse experiences leave biological traces in children

By Rachel Yehuda

Illustration by Joyce Hesselberth



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AFTER THE TWIN TOWERS OF THE WORLD TRADE CENTER collapsed on September 11, 2001, in a haze of horror and smoke, clinicians at the Icahn School of Medicine at Mount Sinai in Manhattan offered to check anyone who'd been in the area for exposure to toxins. Among those who came in for evaluation were 187 pregnant women. Many were in shock, and a colleague asked if I could help diagnose and monitor them. They were at risk of developing posttraumatic stress disorder, or PTSD—experiencing flashbacks, nightmares, emotional numbness or other psychiatric symptoms for years afterward. And were the fetuses at risk?

My trauma research team quickly trained health professionals to evaluate and, if needed, treat the women. We monitored them through their pregnancies and beyond. When the babies were born, they were smaller than usual—the first sign that the trauma of the World Trade Center attack had reached the womb. Nine months later we examined 38 women and their infants when they came in for a wellness visit. Psychological evaluations revealed that many of the mothers had developed PTSD. And those with PTSD had unusually low levels of the stress-related hormone cortisol, a feature that researchers were coming to associate with the disorder.

Surprisingly and disturbingly, the saliva of the nine-month-old babies of the women with PTSD also showed low cortisol. The effect was most prominent in babies whose mothers had been in their third trimester on that fateful day. Just a year earlier a team I led had reported low cortisol levels in adult children of Holocaust survivors, but we'd assumed that it had something to do with being raised by parents who were suffering from the long-term emotional consequences of severe trauma. Now it looked like trauma leaves a trace in offspring even before they are born.

In the decades since, research by my group and others has confirmed that adverse experiences may influence the next generation through multiple pathways. The most apparent route runs through parental behavior, but influences during gestation and even changes in eggs and sperm may also play a role. And all these channels seem to involve epigenetics: alterations in the way that genes function. Epigenetics potentially explains why effects of trauma may endure long after the immediate threat is gone, and it is also implicated in the diverse pathways by which trauma is transmitted to future generations.

The implications of these findings may seem dire, suggesting that parental trauma predisposes offspring to be vulnerable to mental health conditions. But there is some evidence that the epigenetic response may serve as an adaptation that might help the children of traumatized parents cope with similar adversities. Or could both possible outcomes be true?

IN THE AFTERMATH

MY FIRST ENCOUNTER with intergenerational transmission of trauma was in the 1990s, soon after my team documented high rates of PTSD among Holocaust survivors in my childhood community in Cleveland. The first study of its kind, it garnered a lot of publicity; within weeks I found myself heading a newly created Holocaust research center at Mount Sinai staffed largely by professional volunteers. The phone was ringing off the hook. The callers weren't all Holocaust survivors, though; most were the adult children of Holocaust survivors. One particularly persistent caller—I'll call him Joseph—insisted that I study people like him. "I'm a casualty of the Holocaust," he claimed.

When he came in for an interview, Joseph didn't look like a casualty of anything. A handsome and wealthy investment banker in an Armani suit, he could've stepped off the pages of a magazine. But Joseph lived each day with a vague sense that something terrible was going to happen and that he might need to flee or fight for his life. He'd been preparing for the worst

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since his early 20s, keeping cash and jewelry at hand and becoming proficient in boxing and martial arts. Lately he was tormented by panic attacks and nightmares of persecution, possibly triggered by reports of ethnic cleansing in Bosnia.

Joseph's parents had met in a displaced-persons camp after surviving several years at Auschwitz, then arrived penniless in the U.S. His father worked 14 hours a day and said very little, never mentioning the war. But almost every night he woke the family with shrieks of terror from his nightmares. His mother spoke endlessly about the war, telling vivid bedtime stories about how relatives had been murdered before her eyes. She was determined that her son succeed, and his decision to remain unattached and childless infuriated her. "I didn't survive Auschwitz so that my own child would end the family line," she'd say. "You have an obligation to me and to history."

We ended up talking to many people like Joseph: adult children of Holocaust survivors who suffered from anxiety, grief, guilt, dysfunctional relationships and intrusions of Holocaust-related imagery. Joseph was right—I needed to study people like him. Because those who were calling us were (in research-speak) self-selecting, we decided to evaluate the offspring of the Holocaust survivors we had just studied in Cleveland. The results were clear. Survivors' adult children were more likely than others to have mood and anxiety disorders, as well as PTSD. Further, many Holocaust offspring also had low cortisol levels—something that we had observed in their parents with PTSD.

FIGHT, FLIGHT—OR FREEZE

WHAT DID IT ALL MEAN? Unraveling the tangle of trauma, cortisol and PTSD has occupied me and many other researchers for the decades since. In the classic fight-or-flight response, identified in the 1920s, a threatening encounter triggers the release of stress hormones such as adrenaline and cortisol. The hormones prompt a cascade of changes, such as quickening the pulse and sharpening the senses to enable the threatened person or animal to focus on and react to the immediate danger. These acute effects were believed to dissipate once the danger receded.

In 1980, however, psychiatrists and other advocates for Vietnam War veterans won a prolonged struggle to get post-traumatic stress included in the third edition of the *Diagnostic and Statistical Manual of Mental Disorders* (*DSM-III*). It was the first official recognition that trauma could have long-lasting effects. But the diagnosis was controversial. Many psychologists believed that its inclusion in the *DSM-III* had been politically, rather than scientifically, driven—in part because there were no scientific explanations for how a threat could continue to influence the body long after it was removed.

Complicating matters, studies of Vietnam veterans were generating perplexing results. In the mid-1980s neuroscientists John Mason, Earl Giller and Thomas Kosten, then all at Yale University, reported that veterans with PTSD had high levels of adrenaline but lower levels of cortisol than patients with other psychiatric diagnoses. Because stress usually causes stress hormones, including cortisol, to rise, many researchers, including myself, were skeptical of these observations. When I joined the Yale laboratory as a postdoctoral fellow a year later, I studied a different group of veterans using other methods for measuring cortisol. To my astonishment, I replicated the finding.

I still couldn't believe that the low cortisol levels had anything to do with trauma. Surely the Holocaust was as terrible as the Vietnam War, I reasoned—and growing up as a rabbi's daughter in a community full of Holocaust survivors, many of them my friends' parents, I'd noticed nothing out of the ordinary about them. I was sure that they didn't have either PTSD or low cortisol, I told my mentor, Giller. "That's a testable hypothesis," he responded. "Why don't you study that, instead of conjecturing?"

So my team of five people landed in Cleveland, along with a centrifuge and other equipment. We stayed in my parents' home, walking door to door to interview people by day and returning to test blood and urine samples in the evening. When the results came in, they were clear: half the Holocaust survivors had PTSD, and those with PTSD had low cortisol. There was no question about it—even if the traumatic experience was long ago, PTSD went hand in hand with low cortisol.

A shape was emerging that connected childhood adversity with low cortisol and the possibility of future PTSD.

But why? And which came first? An important clue came from a 1984 review by Allan Munck and other researchers at the Geisel School of Medicine at Dartmouth. They noted that among stress hormones, cortisol played a special, regulatory role. High levels of stress hormones, if sustained for a long time, harm the body in multiple ways, weakening the immune system and increasing susceptibility to problems such as hypertension. But in a context of acute trauma, cortisol may paradoxically also have a protective effect. It shuts down the release of stress hormones—including itself—reducing the potential damage to organs and the brain. Such a trauma-induced feedback loop could conceivably reset the cortisol "thermostat" to a lower level.

I picked up another piece of the puzzle and placed it. In the early 1990s we'd shown that Vietnam veterans were more likely to develop PTSD if they'd been abused as children. Slowly a shape was emerging that connected intense childhood adversity—a period of "freeze" because a child usually cannot fight or flee—with low cortisol and the possibility of future PTSD. We studied people who'd been raped or who'd been in auto accidents when they came into emergency rooms, finding that those with lower cortisol levels were more likely to develop PTSD after the attack or accident.

Could low cortisol levels have been present before the event that brought them into the emergency room? I wondered. If someone with low cortisol was subjected to a traumatic experience, we reasoned, the cortisol levels in their bodies might be too low to tamp down the stress reaction. Adrenaline levels might then shoot way up, searing the memory of the new trauma into the brain—from where it might later surface as flashbacks or nightmares. Perhaps low cortisol marked a vulnerability to developing PTSD.

The study of Holocaust offspring supported this conjecture. Children of Holocaust survivors with PTSD tended to have low

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cortisol even if they did not have their own PTSD. As we'd suspected, low cortisol seemed related to vulnerability to PTSD.

THE FEEDBACK LOOP

BUT WHAT MECHANISM connected trauma exposure to low cortisol to future PTSD? We began a series of studies to answer this question. Significantly, we found that Vietnam veterans with PTSD had a greater number of glucocorticoid receptors. These are proteins to which cortisol binds to exert its diverse influences. That suggested a greater sensitivity to cortisol: a small increase in the hormone's concentration would precipitate a disproportionate physiological reaction. But it wasn't until we looked more closely at the molecular underpinnings of cortisol functioning—in part by examining epigenetics—that we understood how exposure to trauma might reset the cortisol feedback loop.

In the 1990s scientists were realizing that the output of our genes is sensitive to factors not written directly into our genetic code. Genes provide the templates for producing proteins. But much like cakes baked using the same ingredients may turn out differently depending on variations in the oven's temperature, how much of those proteins gets produced, or "expressed," depends on the environment. The discovery gave rise to epigenetics, the study of what influences gene expression and how. It proved crucial to understanding both the neurobiology of PTSD and the intergenerational effects of trauma.

Epigeneticists explore the switches that turn gene expression on and off. One such mechanism, called methylation, involves a methyl group—a methane molecule that is missing one of its four hydrogen atoms, leaving a chemical bond free to attach to another atom or molecule. Methylation is a process by which, in the presence of specific enzymes, methyl groups attach to key sites on a strand of DNA or within the complex of DNA and proteins known as chromatin. By occupying these sites like roadblocks on a highway, methyl groups can alter transcription, a basic step in gene expression where a piece of RNA is made from a DNA template. Increased methylation generally impedes RNA transcription, whereas less methylation enhances transcription. These changes are enduring in that they survive normal cell division and require specific enzymes for their removal.

In 2015 our group became one of the first to pinpoint epigenetic changes on stress-related genes of veterans with PTSD. These alterations partially explained why trauma's effects were so persistent, lasting for decades. Specifically we observed reduced methylation in an important region of *NR3C1,* a gene that encodes the glucocorticoid receptor, likely increasing the sensitivity of these receptors.

This epigenetic modification suggests a potential explanation for how trauma might reset cortisol levels. The body regulates the stress response through a complicated feedback mechanism. A rise in cortisol levels will prompt the body to produce less of the hormone, which may drive up the numbers and responsiveness of glucocorticoid receptors. Given the epigenetic and other changes occurring with sustained responses to trauma, the feedback loop might become recalibrated. In people who have already endured trauma, their stress systems might be sensitized and their cortisol levels diminished—increasing their adrenaline response to further trauma and leading to PTSD.

EPIGENETIC INHERITANCE

COULD SOME OF THESE epigenetic changes in trauma survivors also be found in the children of trauma survivors? Finding low cortisol in the 9/11 babies back in 2002 had told us that we'd been thinking about some things all wrong. We'd assumed all along that trauma was behaviorally transmitted: Joseph's problems seemed to result from the stressful, bereaved atmosphere in his childhood home. But now it looked like the uterine environment also played a role. So did the sex of the traumatized parent.

In our early studies of Holocaust offspring, we had selected only those people with two parents who were Holocaust survivors. We redid the studies to figure out if the sex of the parent mattered—and it did. Those whose mother (or both parents) had PTSD tended to exhibit lower cortisol levels and showed evidence of more sensitive glucocorticoid receptors. In contrast, those whose fathers, but not mothers, had PTSD showed the opposite effect.

Taking a closer look, we again discovered lower methylation within the glucocorticoid receptor gene, *NR3C1,* in Holocaust offspring whose mothers, or both parents, had PTSD. These changes mirrored what we'd observed in the maternal survivors themselves. But in offspring with only paternal PTSD, we observed more methylation—the opposite effect. These findings raised the possibility that PTSD in mothers and fathers might lead to different epigenetic changes on the glucocorticoid receptor in children.

In a second series of studies beginning in 2016, we examined methylation within another gene, *FKBP5,* which encodes a protein involved in regulating the ability of the glucocorticoid receptor to bind cortisol. The findings showed related methylation patterns within the *FKBP5* gene in both Holocaust parents and their children. But because of the small number of participants in that study—by this time it was difficult to find many living Holocaust survivors who could participate with their offspring—we couldn't examine how factors such as the parents' PTSD status might contribute to *FKBP5* methylation.

We were able to replicate and extend this work in a substantially larger sample of just the Holocaust offspring, however. In 2020 we reported lower levels of *FKBP5* methylation in the adult children whose mothers—and not fathers—were exposed to the Holocaust during childhood. This effect was independent of whether the mother had PTSD. It suggested that trauma might have affected the mothers' eggs decades before her children were conceived, while she was herself a child.

Given the obvious difficulties in studying generations of people, scientists often resort to animal studies to explore epigenetic transmission. In 2014 Brian Dias and Kerry Ressler, both at the Emory University School of Medicine, reported an intergenerational epigenetic pathway that ran through sperm. They gave a male mouse a mild electric shock as it smelled a cherry blossom scent, stimulating a fear response to the odor. The response was accompanied by epigenetic changes in its brain and sperm. Intriguingly, the male offspring of the shocked mice demonstrated a similar fear of cherry blossoms—as well as epigenetic changes in their brain and sperm—without being exposed to the shock. These effects were passed down for two generations. In other words, the lesson the grandfather mouse learned, that the cherry blossom scent means danger, was transmitted to its son and grandson.

In a study published in 2020, my colleagues and I experi-

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mented with genome-wide gene expression, a tool that can identify links between protein expression and specific conditions across the entire human genome. With this approach, we again observed distinct patterns of gene expression linked with maternal and paternal trauma exposure and PTSD.

IN THE WOMB

APART FROM ALTERING the eggs and sperm that encapsulate our genetic inheritance, sometimes decades before conception, trauma also seems to influence the uterine environment. Meticulous studies of the offspring of women who were pregnant during the Dutch Famine—a six-month period during World War II when the Nazis blocked the food supply to the Netherlands, causing widespread starvation—provided an early indication of in utero effects. Researchers discovered that the combined effects of extreme stress and nutritional deprivation, such as deficits in metabolism and susceptibility to cardiovascular illness, depended on the trimester of exposure.

The 9/11 babies were also impacted in the womb, with those in the third trimester having significantly lower cortisol levels. What this condition meant for their future development I sadly never found out. At the wellness visit, mothers who had PTSD (and low cortisol) were more likely to report that their nine-month-olds were unusually anxious and afraid of strangers. But we didn't get the funding to follow the babies into adulthood.

How might the uterine environment leave a trauma trace in the offspring? Our work on Holocaust survivors and their adult children provided some clues. The story is again complicated, and it involves an enzyme known as 11-beta-hydroxysteroid dehydrogenase type 2 (11β-HSD2). Holocaust survivors had lower levels of the enzyme than those who hadn't lived through the Holocaust—and such effects were particularly pronounced in those who were the youngest during World War II. The enzyme is normally concentrated in the liver, kidneys and brain. Under conditions of food deprivation, however, the body can lower levels of 11β-HSD2 to increase metabolic fuel in the interest of promoting survival. In adults, the enzyme level will return to what it was when there is no more starvation, but in children, the level may remain low. Our findings suggested that 11β-HSD2 levels might have been altered during childhood when Holocaust survivors were exposed to long periods of malnourishment; the change persisted well into old age.

In the children of women who were Holocaust survivors, however, we saw quite the opposite: 11β-HSD2 levels were higher than in Jewish control subjects. The result might seem contradictory, but there is a logic to it. During pregnancy, 11β-HSD2 also acts in the placenta, protecting the fetus from exposure to circulating maternal cortisol, which can be toxic to the developing brain. The enzyme, which is particularly active in the third trimester, converts maternal cortisol into an inactive form, creating a kind of chemical shield in the placenta that protects the fetus from the hormone's harmful effects. The high levels of this enzyme in the offspring of Holocaust survivors may thus reflect an adaptation, an effort to protect the fetus from the lowered 11β-HSD2 levels in their mothers.

All of this means that offspring are not always passive recipients of their parents' scars. Just as a parent was able to survive trauma by means of biological adaptations, offspring can sometimes adapt to the biological impact of their parents' trauma.

How traumatized parents interact with their children, of course, also influences their development. One of the most powerful nonfiction accounts of growing up with Holocaust survivor parents was Art Spiegelman's serialized graphic novel *Maus;* it broke through a cultural barrier, helping others to open up about their suffering. Many psychologists and neuroscientists have examined the traumatized family, finding ever more subtleties, and the story will continue to unfold for decades to come.

An important question is whether epigenetic alterations in stress-related genes, particularly those reflected in the offspring of traumatized parents, are necessarily markers of vulnerability or whether they may reflect a mechanism through which offspring become better equipped to cope with adversity. This is an area we're actively exploring.

> Epigenetic inheritances may represent the body's attempts to prepare offspring for challenges similar to those encountered by their parents.

It is tempting to interpret epigenetic inheritance as a story of how trauma results in permanent damage. Epigenetic influences might nonetheless represent the body's attempts to prepare offspring for challenges similar to those encountered by their parents. As circumstances change, however, the benefits conferred by such alterations may wane or even result in the emergence of novel vulnerabilities. Thus, the survival advantage of this form of intergenerational transmission depends in large part on the environment encountered by the offspring themselves.

Moreover, some of these stress-related and intergenerational changes may be reversible. Several years ago we discovered that combat veterans with PTSD who benefited from cognitive-behavioral psychotherapy showed treatment-induced changes in *FKBP5* methylation. The finding confirmed that healing is also reflected in epigenetic change. And Dias and Ressler reconditioned their mice to lose their fear of cherry blossoms; the offspring conceived after this "treatment" did not have the cherry blossom epigenetic alteration, nor did they fear the scent. Preliminary as they are, such findings represent an important frontier in psychiatry and may suggest new avenues for treatment.

The hope is that as we learn more about the ways catastrophic experiences have shaped both those who lived through those horrors and their descendants, we will become better equipped to deal with dangers now and in the future, facing them with resolution and resilience. SA

Rachel Yehuda is a professor of psychiatry and neuroscience and director of the Center for Psychedelic Psychotherapy and Trauma Research at the Icahn School of Medicine at Mount Sinai. She is also director of mental health at the James J. Peters Veterans Affairs Medical Center.

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The Science of Abortion Restrictions

The researcher who led a landmark study explains the devastating health and financial effects of being denied an abortion

By Tanya Lewis

A DRAFT OF A U.S. SUPREME COURT opinion leaked in May 2022 suggested the nation's highest court was poised to overturn *Roe v. Wade,* the landmark ruling that guaranteed the right to an abortion. The opinion was first reported by Politico. After it was officially issued in June, many U.S. states passed laws—or enforced existing ones—greatly restricting access to the procedure. One of the most comprehensive studies conducted to date shows that those who are denied an abortion—and thus forced to go through with an unwanted pregnancy—experience lasting negative effects on their health, well-being and finances.

A Supreme Court opinion along these lines had been expected, but the news nonetheless startled researchers who study reproductive rights. "The callousness of the decision is shocking," says Diana Greene Foster, a professor of obstetrics, gynecology and reproductive sciences at the University of California, San Francisco.

Foster led the well-known Turnaway Study, a large and comprehensive investigation comparing women who received an abortion with women who were just past the legal gestational cutoff and were denied one. The study found that women denied the procedure were more likely to experience negative health impacts—including worse mental health—than women who received one. The former were also more likely to face worse financial outcomes, including poor credit, debt and bankruptcy. (The study did not include pregnant people who did not identify as women.)

In May, before the Supreme Court had issued its final opinion, SCIENTIFIC AMERICAN spoke to Foster about the Turnaway Study's findings and how overturning Roe was likely to impact people seeking abortions in this country.

[*An edited transcript of the interview follows.*]

What is your reaction to the leaked draft opinion that suggests Roe will be overturned?

This is the decision that I was anticipating because the abortion opinions of the justices are pretty well known. But the fact that it's leaked is shocking, unprecedented. And the callousness of the decision is kind of shocking, too—you know, the idea that the Constitution doesn't protect people's decision-making around something so fundamental as childbearing, when it has such huge impacts on their health and their ability to support themselves and their children.

And the idea that [*Roe v. Wade*] might have been wrongly decided—and how we would know that is that there is division within our country—that's not the principles of our Constitution. It's not about the division of our country; it's about the well-being of individuals. And so it's just the wrong motives.

Can you describe the Turnaway Study and what its main findings were?

The Turnaway Study followed people who sought abortions—some who got their wanted abortion and some who were too far along and were denied. It looked at "What is the impact of having access to abortion on people's health and well-being?" And what we see is very large health burdens, greater health risks for people who carry pregnancies to term. That's consistent with the medical literature. We see

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WOMAN CRIES while kneeling in front of the U.S. Supreme Court in Washington, D.C., on May 2, 2022. The Supreme Court struck down the right to abortion in the country with a majority opinion issued on June 24, 2022, shredding nearly 50 years of constitutional protections.

greater complications from childbirth than from abortion, and in fact, two women in the study died after giving birth.

In what other ways did being denied an abortion impact women and families?
We see economic hardship for people who had a child before they were ready, and we measure that through self-reported living in poverty—their income relative to household size—and we can also see it when we look at their credit reports. We can see that people who sought abortions had the same credit scores prior to the pregnancy, and after one group gave birth … you can see in their credit records, you can see in their public financial records, that the group denied abortions experienced greater bankruptcies, evictions and debt than other people who received their wanted abortion.

We actually see more economic hardship for children, too. Often people say their reason for getting an abortion is to take care of the kids they already have. And [among those who are denied an abortion] we see those existing children are more likely to live in poverty [and] less likely to achieve developmental milestones than the children whose mothers were able to get an abortion.

People often think that those seeking an abortion don't want to have kids at all. Is that true?
Many people who have abortions want to have children later, under better circumstances. And when they do—when they go and get an abortion and then go on and have a baby—we see those babies do better than children born because their mom was denied an abortion, in terms of the mom's emotional bond with the child, the kids' economic well-being, the chance that they live in a house with just enough money to pay for food and health.

Are the people impacted by restrictive abortion laws disproportionately people of lower socioeconomic status?
Yes.

Do you think the Supreme Court has ignored the science and the research on abortion?
I don't know that. I do know that when the case was heard, Supreme Court Justice John Roberts explicitly said, "[Put the] data aside." So that is not a good sign for him ruling on anything but ideological grounds—to not actually look at the evidence about how this affects families and decide just to do this on political or religious grounds.

Have any amicus briefs in the current Supreme Court case,* Dobbs v. Jackson Women's Health Organization, *cited your research?
We have one amicus brief by social scientists. And there are two others that heavily cite my work—one by public health researchers and one by economists. And there's a whole amicus brief by the other side that is … just an attempt to take

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down the Turnaway Study, but their criticisms are almost absurd.

They don't understand that, you know, people having unintended pregnancies, how common it is and the circumstances.

Some studies looking at the effects of getting an abortion have compared people who had a child they wanted with those who sought an abortion. Is that a false comparison?

The people who wanted their child had better outcomes going in. It's not different people; it's people at different points—the same people under different circumstances. If you give someone a wanted abortion, they can later be the kind of person who can have a kid under circumstances that they do want. It's not that they're different people having kids; it's that people have to be able to have kids when they're ready.

There is a paper that actually compares outcomes for people who were forced to carry their pregnancy to term with the people who got an abortion and were able to have kids later on. Not all those subsequent pregnancies were planned in advance. Most of them weren't. But the person decided to carry that pregnancy to term, and the economic outcomes were better for that child, and the emotional outcomes were better as well.

In your study, did the women who were denied legal abortions try to get them anyway?

In our study, they didn't, mostly. They either traveled vast distances and got an abortion somewhere else, or they had a baby. But the vast majority of them had the baby because there were very few places that would do abortions.

Based on your research, what impact will this Supreme Court ruling have on pregnant people seeking abortions?

For people who are unable to get their abortion because the Supreme Court just lets states ban abortions, we're going to see worse physical health, greater economic hardship, lower achievement of aspirational plans, kids raised in more precarious economic circumstances, and people's lives upended. SA

Tanya Lewis is a senior editor at *Scientific American* who covers health and medicine.

Coverage Savings

Universal health care could have saved more than 330,000 lives during COVID

By Rachel Nuwer

Americans spend more on health care than people in any other nation. Yet in any given year, the piecemeal nature of the American medical insurance system causes many preventable deaths and unnecessary costs. Not surprisingly, COVID only exacerbated this already dire public health issue, as evidenced by the U.S.'s elevated mortality, compared with that of other high-income countries.

A recent study quantified the severity of the impact of the pandemic on Americans who did not have access to health insurance. According to findings published in June 2022 in the *Proceedings of the National Academy of Sciences USA,* from the pandemic's beginning until mid-March 2022, universal health care could have saved more than 338,000 lives from COVID alone. The U.S. also could have saved $105.6 billion in health-care costs associat-

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A WOMAN walks among a field of some 660,000 white flags, representing the number of U.S. lives lost at that time to COVID, at the National Mall in Washington, D.C., on September 16, 2021.

Rod Lamkey/CNP/Sipa USA/Alamy Stock Photo

ed with hospitalizations from the disease—on top of the estimated $438 billion that could be saved in a nonpandemic year.

"Health-care reform is long overdue in the U.S.," says the study's lead author Alison Galvani, director of the Center for Infectious Disease Modeling and Analysis at the Yale School of Public Health. "Americans are needlessly losing lives and money."

People who do not have insurance usually do not have a primary care doctor, which means they are more likely to suffer from preventable diseases such as type 2 diabetes. They also tend to wait longer to see a doctor when they fall ill. These two factors already contribute to higher mortality rates in nonpandemic years, and they compounded the impacts of COVID. Comorbidities exacerbate the risk of the disease, and waiting to seek care increases the likelihood of transmission to other people.

Prior to the pandemic, 28 million American adults were uninsured, and nine million more lost their insurance as a result of unemployment because of COVID. "Many Americans feel secure in having good health insurance from their employer, but employer-based insurance can be cut off when it is needed most," Galvani points out.

In the study, Galvani's team compared the mortality risks of COVID among people with and without insurance, as well as their risks of all other causes of death. The researchers compiled population characteristics of all uninsured Americans during the pandemic, taking into account things such as age-specific life expectancy and the elevation in mortality associated with a lack of insurance. They calculated that 131,438 people could have been saved from dying of COVID in 2020 alone. And more than 200,000 additional deaths from COVID could have been averted between then and the end of the study, bringing the total through March 12, 2022, to more than 338,000.

The researchers also estimated the cost to insure the entire U.S. population—and the savings that measure would produce. They found that a single-payer health-care system would generate savings in three ways: more efficient investment in preventive care; lowered administrative costs; and increased negotiating power for pharmaceuticals, equipment and fees. This would have produced a net savings of $459 billion in 2020 and $438 billion in a nonpandemic year, the authors found. "Medicare for All would be both an economic stimulus and lifesaving transformation of our health-care system," Galvani says. "It will cost people far less than the status quo."

Galvani and her colleagues' findings are "very convincing," and "the methodology strikes me as exactly right," says Robert Reich, a professor of public policy at the University of California, Berkeley, who was not involved in the work. "The savings estimates are consistent with every other estimate I've seen."

Ann Keller, an associate professor of health policy and management also at U.C. Berkeley, suspects, however, that the study likely underestimates the deaths that could have been avoided through universal health care because it does not consider the lower rates of chronic disease that often accompany single-payer systems. "Having consistent access to care can prevent chronic disease from occurring and can ensure that patients who develop chronic disease have it better managed," says Keller, who was also not involved with the research. "I would think that, if one took that into account, the estimates of avoided deaths would be greater than the numbers reported here."

Whatever the exact figures, Galvani says the message that comes out of the study is clear: "Universal single-payer health care is both economically responsible and morally imperative." SA

Rachel Nuwer is a freelance science journalist and author who regularly contributes to *Scientific American*, the *New York Times* and *National Geographic*, among other publications.

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Voyagers to the Stars

The farthest-flung spacecraft in history are entering a new realm—interstellar space

By Tim Folger

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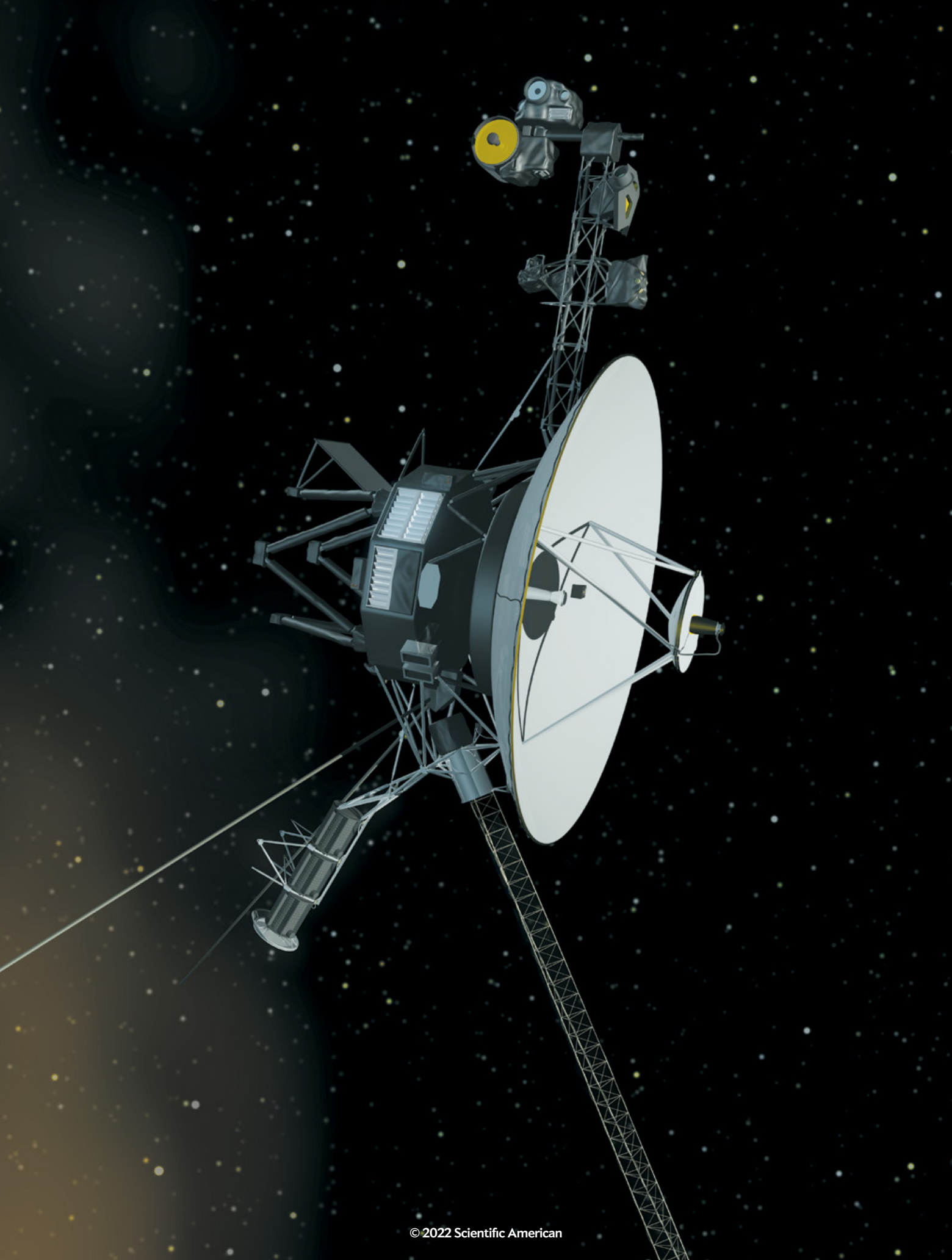

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IF THE STARS HADN'T ALIGNED, TWO OF THE most remarkable spacecraft ever launched never would have gotten off the ground. In this case, the stars were actually planets—the four largest in the solar system. Some 60 years ago they were slowly wheeling into an array that had last occurred during the presidency of Thomas Jefferson in the early years of the 19th century. For a while the rare planetary set piece unfolded largely unnoticed. The first person to call attention to it was an aeronautics doctoral student at the California Institute of Technology named Gary Flandro.

It was 1965, and the era of space exploration was barely underway—the Soviet Union had launched Sputnik 1, the first artificial satellite, only eight years earlier. Flandro, who was working part-time at NASA's Jet Propulsion Laboratory in Pasadena, Calif., had been tasked with finding the most efficient way to send a space probe to Jupiter or perhaps even out to Saturn, Uranus or Neptune. Using a favorite precision tool of 20th-century engineers—a pencil—he charted the orbital paths of those giant planets and discovered something intriguing: in the late 1970s and early 1980s, all four would be strung like pearls on a celestial necklace in a long arc with Earth.

This coincidence meant that a space vehicle could get a speed boost from the gravitational pull of each giant planet it passed, as if being tugged along by an invisible cord that snapped at the last second, flinging the probe on its way. Flandro calculated that the repeated gravity assists, as they are called, would cut the flight time between Earth and Neptune from 30 years to 12. There was just one catch: the alignment happened only once every 176 years. To reach the planets while the lineup lasted, a spacecraft would have to be launched by the mid-1970s.

As it turned out, NASA would build *two* space vehicles to take advantage of that once-in-more-than-a-lifetime opportunity. Voyager 1 and Voyager 2, identical in every detail, were launched within 15 days of each other in the summer of 1977. After more than 45 years in space, they are still functioning, sending data back to Earth every day from beyond the solar system's most distant known planets. They have traveled farther and lasted longer than any other spacecraft in history. And they have crossed into interstellar space, according to our best understanding of the boundary between the sun's sphere of influence and the rest of the galaxy. They are the first human-made objects to do so, a distinction they will hold for at least another few decades. Not a bad record, all in all, considering that the Voyager missions were originally planned to last just four years.

Early in their travels, four decades ago, the Voyagers gave astonished researchers the first close-up views of the moons of Jupiter and Saturn, revealing the existence of active volcanoes and fissured ice fields on worlds astronomers had thought would be as inert and crater-pocked as our own moon. In 1986 Voyager 2 became the first spacecraft to fly past Uranus; three years later it passed Neptune. So far it is the only spacecraft to have made such journeys. Now, as pioneering inter-

NASA/JPL-Caltech (*preceding pages* and *this page*)

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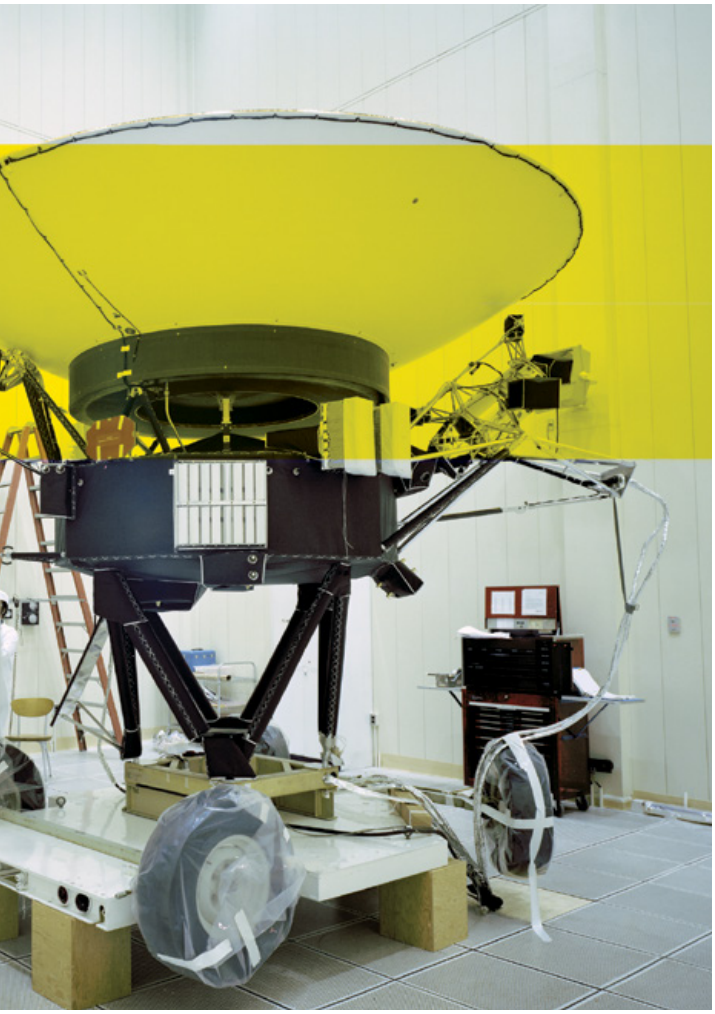

READY FOR LAUNCH: Voyager 2 undergoes testing at NASA's Jet Propulsion Laboratory before its flight (*left*). The spacecraft lifted off on August 20, 1977.

NASA/JPL-Caltech

stellar probes more than 12 billion miles from Earth, they're simultaneously delighting and confounding theorists with a series of unexpected discoveries about that uncharted region.

Their remarkable odyssey is finally winding down. Over the past few years NASA has shut off heaters and other nonessential components, eking out the spacecraft's remaining energy stores to extend their unprecedented journeys to about 2030. For the Voyagers' scientists, many of whom have worked on the mission since its inception, it is a bittersweet time. They are now confronting the end of a project that far exceeded all their expectations.

"We're at 44 and a half years," says Ralph McNutt, a physicist at the Johns Hopkins University Applied Physics Laboratory (APL), who has devoted much of his career to the Voyagers. "So we've done 10 times the warranty on the darn things."

THE STARS MAY have been cooperating, but at first, Congress wasn't. After Flandro's report, NASA drew up plans for a so-called Grand Tour that would send as many as five probes to the four giant planets and Pluto. It was ambitious. It was expensive. Congress turned it down. "There was this really grand vision," says Linda Spilker, a JPL planetary scientist who started working on the Voyager missions in 1977, a few months before their launch. "Because of cost, it was whittled back."

Congress eventually approved a scaled-down version of the Grand Tour, initially called Mariner Jupiter-Saturn 1977, or MJS 77. Two spacecraft were to be sent to just two planets. Nevertheless, NASA's engineers went about designing, somewhat surreptitiously, vehicles capable of withstanding the rigors of a much longer mission. They hoped that once the twin probes proved themselves, their itinerary would be extended to Uranus, Neptune, and beyond.

"Four years—that was the prime mission," says Suzanne Dodd, who, after a 20-year hiatus from the Voyager team, returned in 2010 as the project manager. "But if an engineer had a choice to put in a part that was 10 percent more expensive but wasn't something that was needed for a four-year mission, they just went ahead and did that. And they wouldn't necessarily tell management." The fact that the scientists were able to build two spacecraft, and that both are still working, is even more remarkable, she adds.

In terms of both engineering and deep-space navigation, this was new territory. The motto "Failure is not

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an option" hadn't yet been coined, and at that time it would not have been apt. In the early 1960s NASA had attempted to send a series of spacecraft to the moon to survey future landing sites for crewed missions. After 12 failures, one such effort finally succeeded.

"In those days we always launched two spacecraft" because the failure rate was so high, said Donald Gurnett, only partly in jest. Gurnett, a physicist at the University of Iowa and one of the original scientists on the Voyager team, was a veteran of 40 other space missions. He spoke with me a few weeks before his death in January 2022. (In an obituary, his daughter Christina said his only regret was that "he would not be around to see the next 10 years of data returning from Voyager.")

When the Voyagers were being built, only one spacecraft had used a gravity assist to reach another planet—the Mariner 10 probe got one from Venus while en route to Mercury. But the Voyagers would be attempting multiple assists with margins of error measured in tens of minutes. Jupiter, their first stop, was about 10 times farther from Earth than Mercury. Moreover, the Voyagers would have to travel through the asteroid belt along the way. Before Voyager there had been a big debate about whether spacecraft could get through the asteroid belt "without being torn to pieces," McNutt says. But in the early 1970s Pioneer 10 and 11 flew through it unscathed—the belt turned out to be mostly empty space—paving the way for Voyager, he says.

To handle all these challenges, the Voyagers, each about the size of an old Volkswagen Beetle, needed some onboard intelligence. So NASA's engineers equipped the vehicles' computers with 69 kilobytes of memory, less

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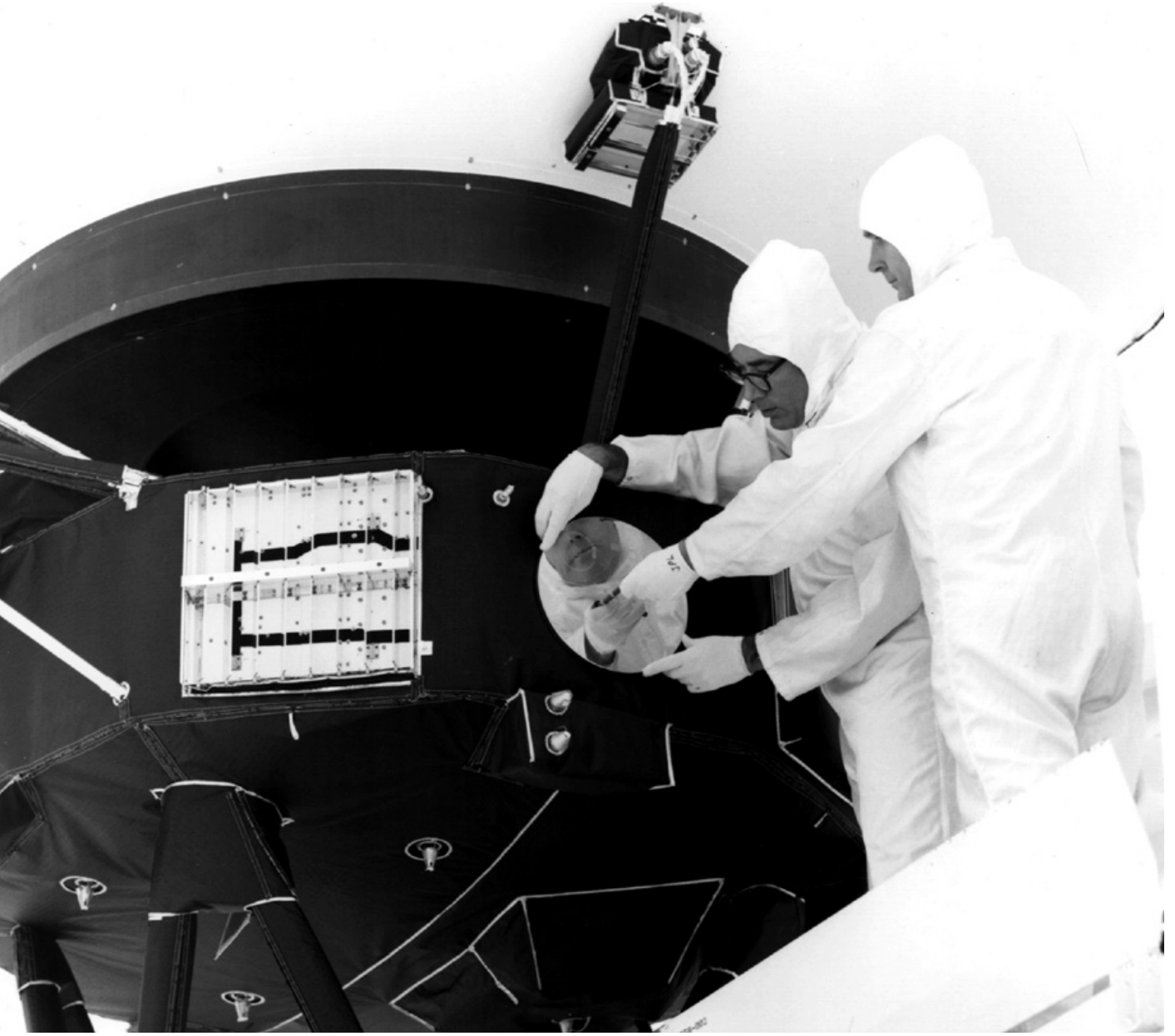

NASA/JPL-Caltech

GOLDEN RECORD: Each Voyager carries a golden record (*left*) of sounds and images from Earth in case the spacecraft are intercepted by an extraterrestrial civilization. Engineers put the cap on Voyager 1's record before its launch (*right*).

than a hundred thousandth the capacity of a typical smartphone. In fact, the smartphone comparison is not quite right. "The Voyager computers have less memory than the key fob that opens your car door," Spilker says. All the data collected by the spacecraft instruments would be stored on eight-track tape recorders and then sent back to Earth by a 23-watt transmitter—about the power level of a refrigerator light bulb. To compensate for the weak transmitter, both Voyagers carry 12-foot-wide dish antennas to send and receive signals.

"It felt then like we were right on top of the technology," says Alan Cummings, a physicist at Caltech and another Voyager OG. "I'll tell you, what was amazing is how quickly that whole thing happened." Within four years the MJS 77 team had built three spacecraft, including one full-scale functioning test model. The spacecraft were rechristened Voyager 1 and 2 a few months before launch.

Although many scientists have worked on the Voyagers over the decades, Cummings can make a unique claim. "I was the last person to touch the spacecraft before they launched," he says. Cummings was responsible for two detectors designed to measure the flux of electrons and other charged particles when the Voyagers encountered the giant planets. Particles would pass through a small "window" in each detector that consisted of aluminum foil just three microns thick. Cummings worried that technicians working on the spacecraft might have accidentally dented or poked holes in the windows. "So they needed to be inspected right before launch," he says. "Indeed, I found that one of them was a little bit loose."

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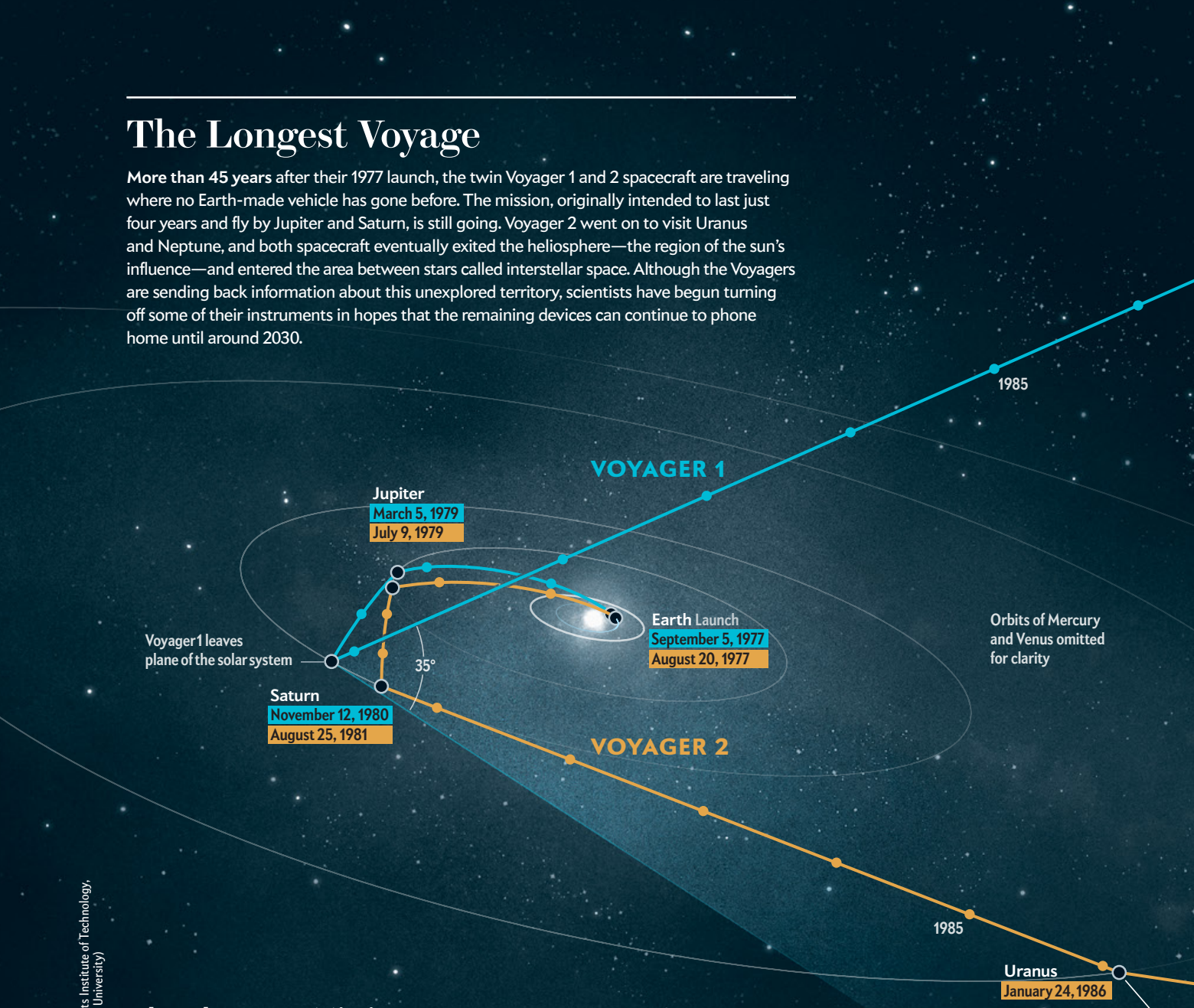
The Longest Voyage

More than 45 years after their 1977 launch, the twin Voyager 1 and 2 spacecraft are traveling where no Earth-made vehicle has gone before. The mission, originally intended to last just four years and fly by Jupiter and Saturn, is still going. Voyager 2 went on to visit Uranus and Neptune, and both spacecraft eventually exited the heliosphere—the region of the sun's influence—and entered the area between stars called interstellar space. Although the Voyagers are sending back information about this unexplored territory, scientists have begun turning off some of their instruments in hopes that the remaining devices can continue to phone home until around 2030.



The Planetary Mission

September 5, 1977
August 20, 1977

LAUNCH

The mission was designed to take advantage of a rare arrangement of the outer planets. Voyager 2 launched first, but reached Jupiter and Saturn after Voyager 1. Shortly after launch, Voyager 1 returned the first photograph of Earth and the moon taken from a spacecraft.

1977–1980
1977–1981

PRIME MISSION

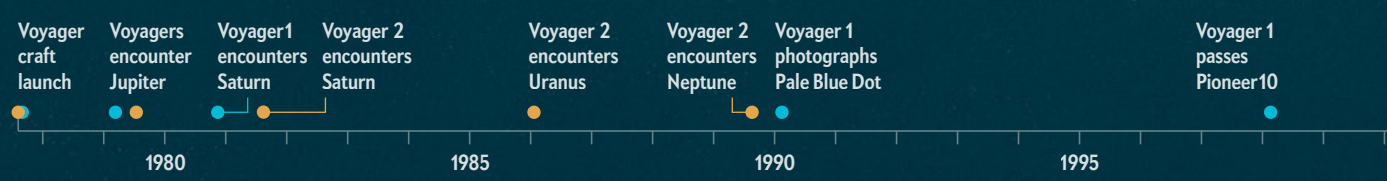
Jupiter and Saturn were planned to be the prime targets of study for both Voyagers. The spacecraft together sent back 52,000 images of Jupiter, Saturn and their moons and discovered 10 new moons.

November 12, 1980

UP AND OUT

After encountering Saturn and its moon Titan, Voyager 1's trajectory was directed northward out of the elliptical plane of the solar system.

VOYAGERS' MILESTONES



Consultants: John Richardson (principal investigator, Voyager Plasma Science, Massachusetts Institute of Technology, Center for Space Research) and Merav Opher (professor, Department of Astronomy, Boston University)

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The Interstellar Mission

1990

February 14, 1990

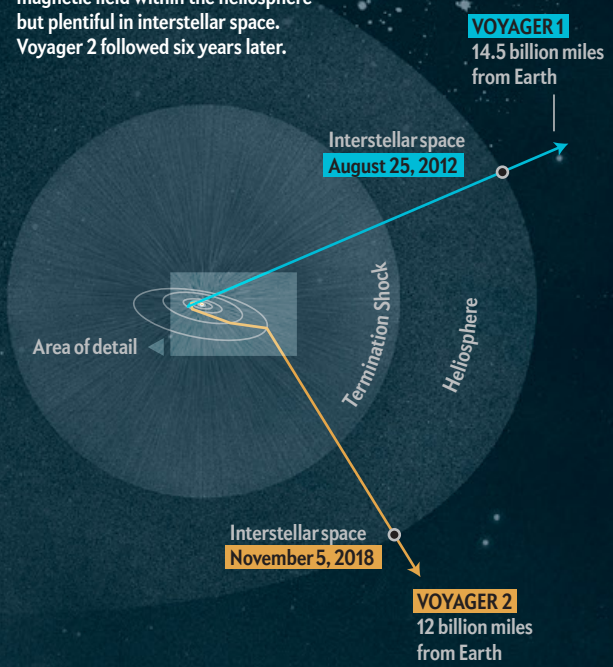
THE PALE BLUE DOT

More than nine years after its encounter with Saturn, 3.7 billion miles from Earth, scientists directed Voyager 1 to turn its camera around and take one last photograph, capturing Earth as "a mote of dust, suspended in a sunbeam," in the words of Voyager scientist Carl Sagan.

August 25, 2012
November 5, 2018

MAKING AN EXIT

Voyager 1 was the first craft to exit the heliosphere, scientists think. This boundary is murky, but its clearest sign came when the vehicle encountered a marked rise in the intensity of cosmic rays, which are blocked by the sun's magnetic field within the heliosphere but plentiful in interstellar space. Voyager 2 followed six years later.



January 24, 1986

OUTER EDGES

The original plan deemed it too expensive for the spacecraft to travel to Uranus and Neptune, but Voyager 2's trajectory preserved the option. After a successful visit to Saturn, the probe appeared to be capable of making it to Uranus with all instruments operating, so NASA provided additional funding.

Neptune
August 25, 1989

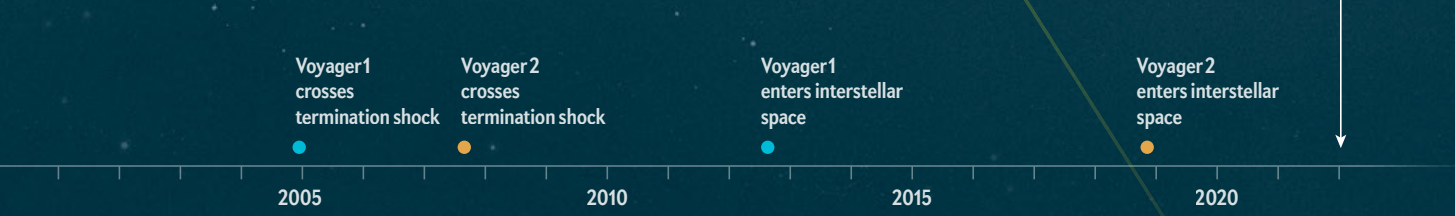
Voyager 2 leaves plane of the solar system

48°

1990

TODAY

The Voyager spacecraft are still operating 45 years after launch, sending back data from billions of miles away. Both are now in interstellar space, a region never before visited by human-made probes.



Graphic by Matthew Twombly and Juan Velasco (5W Infographic)

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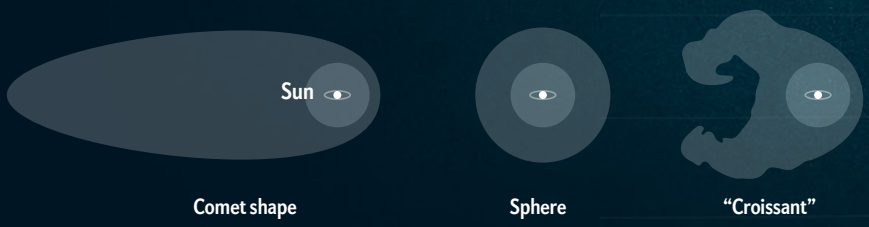
Protective Bubble

Our part of the solar system is encased in a bubble called the heliosphere, a region where the solar wind of charged particles that flows from the sun carries the sun's magnetic field with it. This area extends to about four times the distance between the sun and Neptune but does not stretch to the full extent of the solar system, which includes the spherical cloud of cometlike objects called the Oort cloud, about halfway to the next star.

BUBBLE SHAPE

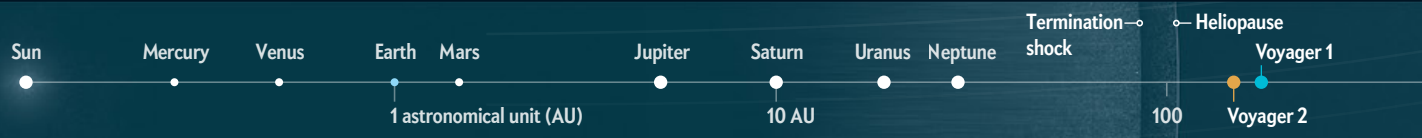
The shape of the heliosphere remains a mystery. Often depicted as a sphere or a cometlike shape with a tail, new research suggests it may be a croissant shape, with a slinkylike magnetic field that funnels the solar wind.



HELIOSPHERE

The solar wind becomes supersonic near the sun. After a point called the termination shock, it slows and follows a shape that is confined by the magnetic fields of the interstellar medium.

ASTRONOMICAL DISTANCES



VOYAGER 1 REACHED JUPITER in March 1979, 546 days after its launch. Voyager 2, following a different trajectory, arrived in July of that year. Both spacecraft were designed to be stable platforms for their vidicon cameras, which used red, green and blue filters to produce full-color images. They hardly spin at all as they speed through space—their rotational motion is more than 15 times slower than the crawl of a clock's hour hand, minimizing the risk of blurred images. Standing-room crowds at JPL watched as the spacecraft started transmitting the first pictures of Jupiter while still about three or four months away from the planet.

"In all of the main conference rooms and in the hallways, they had these TV monitors set up," Spilker says. "So as the data came down line by line, each picture would appear on a monitor. The growing anticipation and the expectation of what we were going to see when we got up really, really close—that was tremendously exciting."

Cummings vividly recalls the day he caught his first glimpse of Jupiter's third-largest moon, Io. "I was going over to a building on the Caltech campus where they were showing a livestream [of Voyager's images]," he says. "I walk in, and there's this big picture of Io, and it's all orange and black. I thought, okay, the Caltech students had pulled a prank, and it's a picture of a poorly made pizza."

Io's colorful appearance was completely unexpected. Before the Voyagers proved otherwise, the assumption had been that all moons in the solar system would be more or less alike—drab and cratered. No one anticipated the wild diversity of moonscapes the Voyagers would discover around Jupiter and Saturn.

The first hint that there might be more kinds of moons in the heavens than astronomers had dreamed of came while the Voyagers were still about a million miles from Jupiter. One of their instruments—the Low-Energy Charged Particle [LECP] detector system—picked up some unusual signals. "We started seeing oxygen and sulfur ions hitting the detector," says Stamatios Krimigis, who designed the LECP and is now emeritus head of the space department at Johns Hopkins APL. The density of oxygen and sulfur ions had shot up by three orders of magnitude compared with the levels measured up to that point. At first, his team thought the instrument had malfunctioned. "We scrutinized the data," Krimigis says, "but there was nothing wrong."

The Voyagers' cameras soon solved the mystery: Io had active volcanoes. The small world—it is slightly larger than Earth's moon—is now known to be the most volcanically active body in the solar system. "The only

Consultants: John Richardson (principal investigator, Voyager Plasma Science, Massachusetts Institute of Technology, Center for Space Research) and Merav Opher (professor, Department of Astronomy, Boston University)

Graphic by Matthew Twombly and Juan Velasco (5W Infographic)

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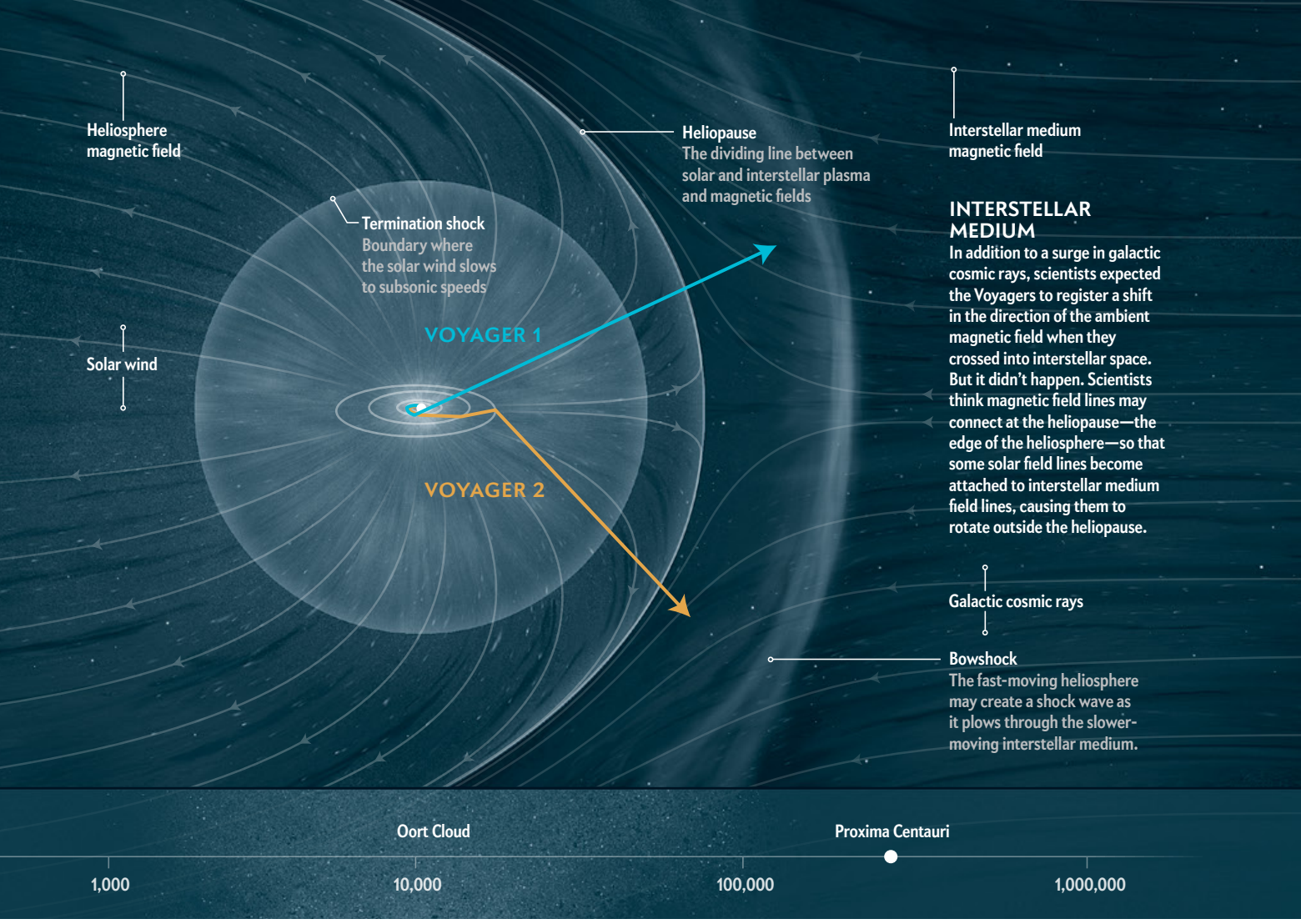
Heliosphere magnetic field
Heliopause
The dividing line between solar and interstellar plasma and magnetic fields
Interstellar medium magnetic field
Termination shock
Boundary where the solar wind slows to subsonic speeds
INTERSTELLAR MEDIUM
In addition to a surge in galactic cosmic rays, scientists expected the Voyagers to register a shift in the direction of the ambient magnetic field when they crossed into interstellar space. But it didn't happen. Scientists think magnetic field lines may connect at the heliopause—the edge of the heliosphere—so that some solar field lines become attached to interstellar medium field lines, causing them to rotate outside the heliopause.
VOYAGER 1
Solar wind
VOYAGER 2
Galactic cosmic rays
Bowshock
The fast-moving heliosphere may create a shock wave as it plows through the slower-moving interstellar medium.
Oort Cloud
Proxima Centauri
1,000
10,000
100,000
1,000,000

active volcanoes we knew of at the time were on Earth," says Edward Stone, who retired in 2022 after 50 years as the project scientist for the Voyager missions. "And here suddenly was a moon that had 10 times as much volcanic activity as Earth." Io's colors—and the anomalous ions hitting Krimigis's detector—came from elements blasted from the moon's volcanoes. The largest of Io's volcanoes, known as Pele, has blown out plumes 30 times the height of Mount Everest; debris from Pele covers an area about the size of France.

Altogether, the Voyagers took more than 33,000 photographs of Jupiter and its satellites. It felt like every image brought a new discovery: Jupiter had rings; Europa, one of Jupiter's 53 named moons, was covered with a cracked icy crust now estimated to be more than 60 miles thick. As the spacecraft left the Jupiter system, they got a farewell kick of 35,700 miles per hour from a gravity assist. Without it they would not have been able to overcome the gravitational pull of the sun and reach interstellar space.

At Saturn, the Voyagers parted company. Voyager 1 hurtled through Saturn's rings (taking thousands of hits from dust grains), flew past Titan, a moon shrouded in orange smog, and then headed "north" out of the plane of the planets. Voyager 2 continued alone to Uranus and Neptune. In 1986 Voyager 2 found 10 new moons around Uranus and added the planet to the growing list of ringed worlds. Just four days after Voyager 2's closest approach to Uranus, however, its discoveries were overshadowed when the space shuttle *Challenger* exploded shortly after launch. All seven of *Challenger*'s crew members were killed, including Christa McAuliffe, a high school teacher from New Hampshire who would have been the first civilian to travel into space.

Three years later, passing about 2,980 miles above Neptune's azure methane atmosphere, Voyager 2 measured the highest wind speeds of any planet in the solar system: up to 1,000 mph. Neptune's largest moon, Triton, was found to be one of the coldest places in the solar system, with a surface temperature of –391 degrees Fahrenheit (–235 degrees Celsius). Ice volcanoes on the moon spewed nitrogen gas and powdery particles five miles into its atmosphere.

Voyager 2's images of Neptune and its moons would have been the last taken by either of the spacecraft had it not been for astronomer Carl Sagan, who was a member of the mission's imaging team. With the Grand Tour officially completed, NASA planned to turn off the cameras on both probes. Although the mission had been extended with the hope that the Voyagers would make it

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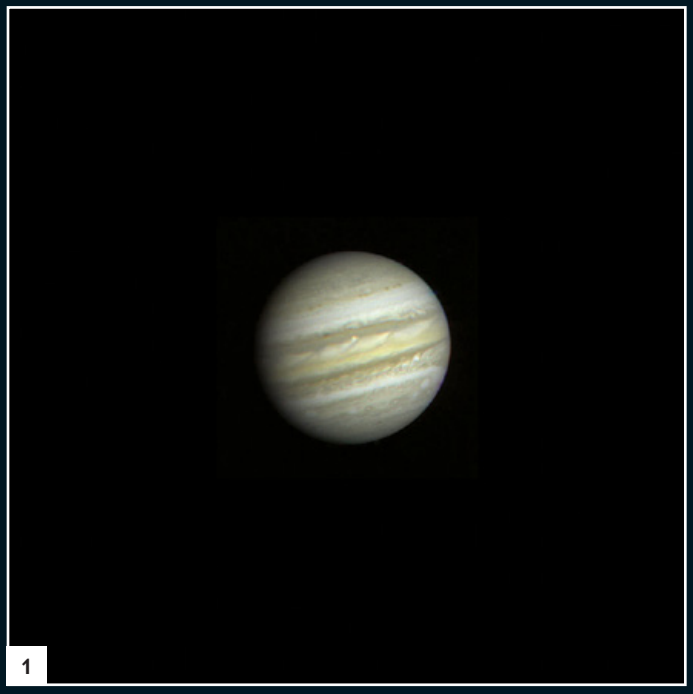
Voyagers' Greatest Hits

The twin spacecraft took a grand tour through the giant planets of the solar system, passing by Jupiter (*1, 2*) and Saturn (*5, 6*) and taking the first close-up views of those planets' moons.

Jupiter's satellite Europa (*3*), for instance, turned out to be covered with ice, and its moon Io (*4*) was littered with volcanoes—discoveries that came as a surprise to scientists who had assumed the moons would be gray and crater-pocked like Earth's. Voyager 2 went on to fly by Uranus (*7*) and Neptune (*8*), and it is still the only probe to have visited there.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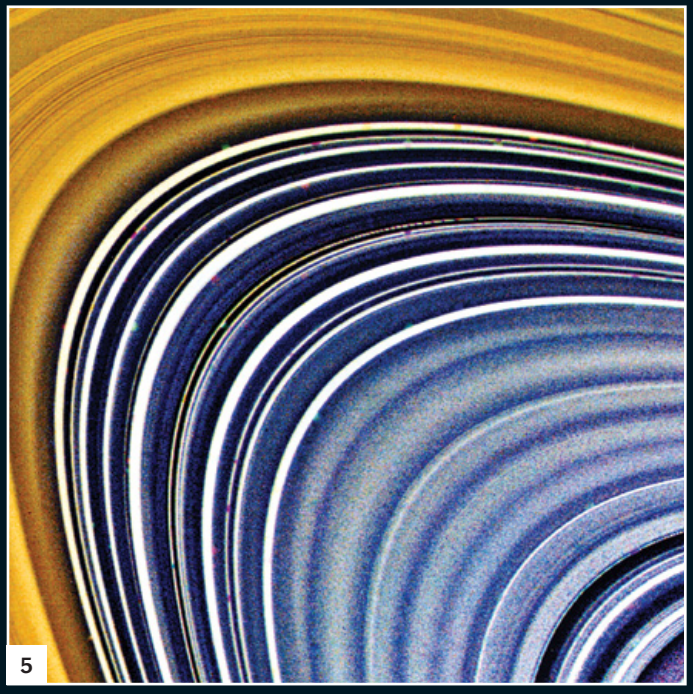
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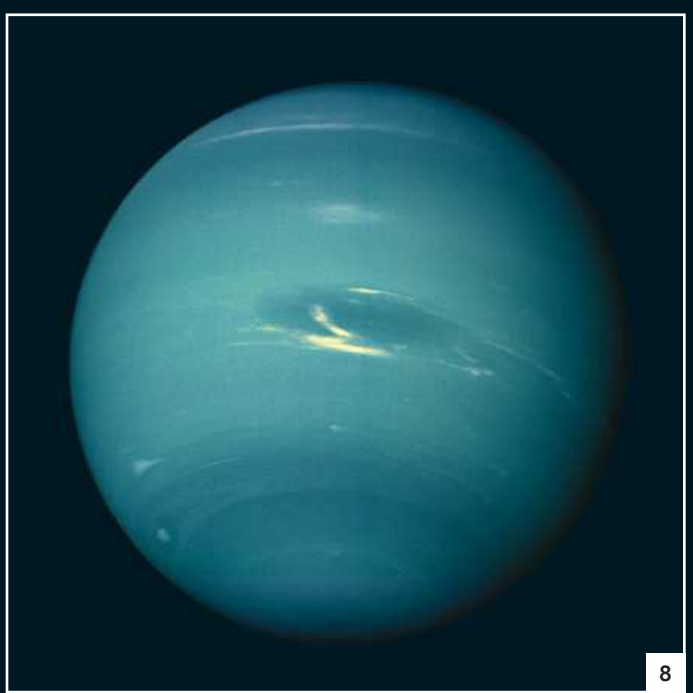
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NASA/JPL (1, 2, 4, 5, 6, 8); NASA/JPL/USGS (3); NASA/JPL-Caltech (7)

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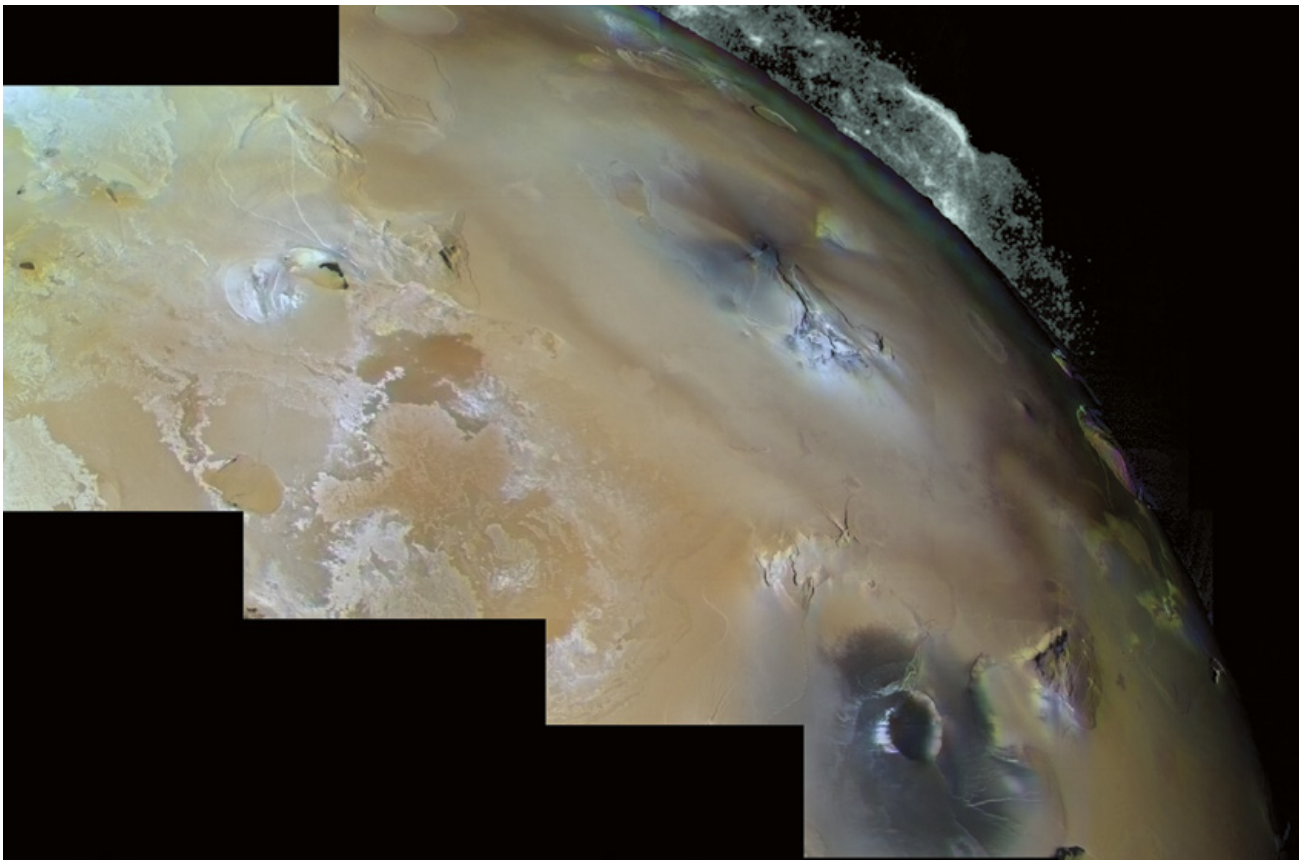

ERUPTION: The discovery of the volcano Pele, shown in this photograph from Voyager 1, confirmed that Jupiter's moon hosts active volcanism.

NASA/JPL/USGS

to interstellar space—it had been officially renamed the Voyager Interstellar Mission—there would be no photo ops after Neptune, only the endless void and impossibly distant stars.

Sagan urged NASA officials to have Voyager 1 transmit one last series of images. So, on Valentine's Day in 1990, the probe aimed its cameras back toward the inner solar system and took 60 final shots. The most haunting of them all, made famous by Sagan as the "Pale Blue Dot," captured Earth from a distance of 3.8 billion miles. It remains the most distant portrait of our planet ever taken. Veiled by wan sunlight that reflected off the camera's optics, Earth is barely visible in the image. It doesn't occupy even a full pixel.

Sagan, who died in 1996, "worked really hard to convince NASA that it was worth looking back at ourselves," Spilker says, "and seeing just how tiny that pale blue dot was."

BOTH VOYAGERS ARE NOW so far from Earth that a one-way radio signal traveling at the speed of light takes almost 22 hours to reach Voyager 1 and just over 18 to catch up with Voyager 2. Every day they move away by another three to four light-seconds. Their only link to Earth is NASA's Deep Space Network, a trio of tracking complexes spaced around the globe that enables uninterrupted communication with spacecraft as Earth rotates. As the Voyagers recede from us in space and time, their signals are becoming ever fainter. "Earth is a noisy place," says Glen Nagle, outreach and communications manager at the Deep Space Network's facility in Canberra, Australia. "Radios, televisions, cell phones—everything makes noise. And so it gets harder and harder to hear these tiny whispers from the spacecraft."

Faint as they are, those whispers have upended astronomers' expectations of what the Voyagers would find as they entered the interstellar phase of the mission. Stone and other Voyager scientists I spoke with cautioned me not to conflate the boundary of interstellar space with that of the solar system. The solar system includes the distant Oort cloud, a spherical collection of cometlike bodies bound by the sun's gravity that may stretch halfway to the closest star. The Voyagers won't reach its near edge for at least another 300 years. But interstellar space lies much closer at hand. It begins where a phenomenon called the solar wind ends.

Like all stars, the sun emits a constant flow of charged particles and magnetic fields—the solar wind. Moving at hypersonic speeds, the wind blows out from the sun like an inflating balloon, forming what astronomers call the heliosphere. As the solar wind billows into space, it pulls the sun's magnetic field along for the ride. Eventually pressure from interstellar matter checks the heliosphere's expansion, creating a boundary—preceded by an enormous shock front, the "termination shock"—with interstellar space. Before the Voyagers' journeys, estimates of the distance to that boundary with interstellar space, known as the heliopause, varied wildly.

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"Frankly, some of them were just guesses," according to Gurnett. One early guesstimate located the heliopause as close as Jupiter. Gurnett's own calculations, made in 1993, set the distance at anywhere from 116 to 177 astronomical units, or AU—about 25 times more distant. (One AU is the distance between Earth and the sun, equal to 93 million miles.) Those numbers, he says, were not very popular with his colleagues. By 1993 Voyager 1 already had 50 AU on its odometer. "If [the heliopause] was at 120 AU, that meant we had another 70 AU to go." If Gurnett was right, the Voyagers, clipping along at about 3.5 AU a year, wouldn't exit the heliosphere for at least another two decades.

That prediction raised troubling questions: would the Voyagers—or the support of Congress—last that long? The mission's funding had been extended on the expectation that the spacecraft would cross the heliopause at about 50 AU. But the spacecraft left that milestone behind without finding any of the anticipated signs of interstellar transit. Astronomers had expected the Voyagers to detect a sudden surge in galactic cosmic rays—high-energy particles sprayed like shrapnel at nearly the speed of light from supernovae and other deep-space cataclysms. The vast magnetic cocoon formed by the heliosphere deflects most low-energy cosmic rays before they can reach the inner solar system. "[It] shields us from at least 75 percent of what's out there," Stone says.

The Voyager ground team was also waiting for the spacecraft to register a shift in the prevailing magnetic field. The interstellar magnetic field, thought to be generated by nearby stars and vast clouds of ionized gases, would presumably have a different orientation from the magnetic field of the heliosphere. But the Voyagers had detected no such change.

Gurnett's 1993 estimates were prescient. Almost 20 years passed before one of the Voyagers finally made it to the heliopause. During that time the mission narrowly survived threats to its funding, and the Voyager team shrank from hundreds of scientists and engineers to a few dozen close-knit lifers. Most of them remain on the job today. "When you have such a long-lived mission, you start to regard people like family," Spilker says. "We had our kids around the same time. We'd take vacations together. We're spanning multiple generations now, and some of the younger people on Voyager were not even born [when the spacecraft] launched."

The tenacity and commitment of that band of brothers and sisters were rewarded on August 25, 2012, when Voyager 1 finally crossed the heliopause. But some of the data it returned were baffling. "We delayed announcing that we had reached interstellar space because we couldn't come to an agreement on the fact," Cummings says. "There was lots of debate for about a year."

Although Voyager 1 had indeed found the expected jump in plasma density—its plasma-wave detector, an instrument designed by Gurnett, inferred an 80-fold increase—there was no sign of a change in the direction of the ambient magnetic field. If the vehicle had crossed from an area permeated by the sun's magnetic field to a region where the magnetic field derived from other stars, shouldn't that switch have been noticeable? "That was a shocker," Cummings says. "And that still bothers me. But a lot of people are coming to grips with it."

When Voyager 2 reached the interstellar shoreline in November 2018, it, too, failed to detect a magnetic field shift. And the spacecraft added yet another puzzle: it encountered the heliopause at 120 AU from Earth—the same distance marked by its twin six years earlier. That did not jibe with any theoretical models, all of which said the heliosphere should expand and contract in sync with the sun's 11-year cycle. During that period the solar wind ebbs and surges. Voyager 2 arrived when the solar wind was peaking, which, if the models were correct, should have pushed the heliopause farther out than 120 AU. "It was unexpected by all the theorists," Krimigis says. "I think the modeling, in terms of the findings of the Voyagers, has been found wanting."

Now that the Voyagers are giving theorists some real field data, their models of the interaction between the heliosphere and the interstellar environment are becoming more complex. "The sort of general picture is that [our sun] emerged from a hot, ionized region" and entered a spotty, partly ionized area in the galaxy, says Gary Zank, an astrophysicist at the University of Alabama in Huntsville. The hot region likely formed in the aftermath of a supernova—some nearby ancient star, or perhaps a few, exploded at the end of its life and heated up the space, stripping electrons off their atoms in the process. The boundary around that region can be thought of as "kind of like the seashore, with all the water and the waves swirling and mixed up. We're in that kind of turbulent region … magnetic fields get twisted up, turned around. It's not like the smooth magnetic fields that theorists usually like to draw," although the amount of turbulence seen can differ depending on the type of observation. The Voyagers' data show little field variation at large scales but many small-scale fluctuations around the heliopause, caused by the heliosphere's influence on the interstellar medium. At some point, it is thought, the spacecraft will leave those roiling shoals behind and at last encounter the unalloyed interstellar magnetic field.

Or maybe that picture is completely wrong. A few researchers believe that the Voyagers have not yet left the heliosphere. "There is no reason for the magnetic fields in the heliosphere and the interstellar medium to have exactly the same orientation," says Len A. Fisk, a space plasma scientist at the University of Michigan and a former NASA administrator. For the past several years Fisk and George Gloeckler, a colleague at Michigan and a longtime Voyager mission scientist, have been working on a model of the heliosphere that pushes its edge out by another 40 AU.

Most people working in the field, however, have been convinced by the dramatic uptick in galactic cosmic rays and plasma density the Voyagers measured. "Given that," Cummings says, "it's very difficult to argue that we're not really in interstellar space. But then again, it's not like

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everything fits. That's why we need an interstellar probe."

McNutt has been pushing for such a mission for decades. He and his colleagues at Johns Hopkins have completed a nearly 500-page report outlining plans for an interstellar probe that would launch in 2036 and potentially could reach the heliosphere within 15 years, shaving 20 years off Voyager 1's flight time. And unlike the Voyager missions, the interstellar probe would be designed specifically to study the outer edge of the heliosphere and its environs. In 2024 the National Academies of Sciences, Engineering, and Medicine will announce its decision about whether the mission should be one of NASA's priorities for the next decade.

An interstellar probe could answer one of the most fundamental questions about the heliosphere. "If I'm looking from the outside, what the devil does this structure look like?" McNutt asks. "We really don't know. It's like trying to understand what a goldfish bowl looks like from the point of view of the goldfish. We [need to] be able to see the bowl from the outside." In some models, as the heliosphere cruises along at 450,000 mph, interstellar matter flows smoothly past it, like water around the bow of a ship, resulting in an overall cometlike shape. One computer model, developed by astronomer Merav Opher and her colleagues at Boston University, predicts that more turbulent dynamics give the heliosphere a shape like a cosmic croissant.

"You can start multiple fights at any good science conference about that," McNutt says, "but it's going to take getting out there and actually making some measurements to be able to see what's going on. It would be nice to know what the neighborhood looks like."

"On the whole," Stamatios Krimigis says, "I think the mission lasted so long because almost everything was hardwired. Today's engineers don't know how to do this.... Voyager is the last of its kind."

SOME THINGS OUTLIVE their purpose—answering machines, VCRs, pennies. Not the Voyagers—they transcended theirs, using 50-year-old technology. "The amount of software on these instruments is slim to none," Krimigis says. "There are no microprocessors—they didn't exist!" The Voyagers' designers could not rely on thousands of lines of code to help operate the spacecraft. "On the whole," Krimigis says, "I think the mission lasted so long because almost everything was hardwired. Today's engineers don't know how to do this. I don't know if it's even possible to build such a simple spacecraft [now]. Voyager is the last of its kind."

It won't be easy to say goodbye to these trailblazing vehicles. "It's hard to see it come to an end," Cummings says. "But we did achieve something really amazing. It could have been that we never got to the heliopause, but we did."

Voyager 2 now has five remaining functioning instruments, and Voyager 1 has four. All are powered by a device that converts heat from the radioactive decay of plutonium into electricity. But with the power output decreasing by about four watts a year, NASA has been forced into triage mode. Two years ago the mission's engineers turned off the heater for the cosmic-ray detector, which had been crucial in determining the heliopause transit. Everyone expected the instrument to die.

"The temperature dropped like 60 or 70 degrees C, well outside any tested operating limits," Spilker says, "and the instrument kept working. It was incredible."

The last two Voyager instruments to turn off will probably be a magnetometer and the plasma science instrument. They are contained in the body of the spacecraft, where they are warmed by heat emitted from computers. The other instruments are suspended on a 43-foot-long fiberglass boom. "And so when you turn the heaters off," Dodd says, "those instruments get very, very cold."

How much longer might the Voyagers last? "If everything goes really well, maybe we can get the missions extended into the 2030s," Spilker says. "It just depends on the power. That's the limiting point."

Even after the Voyagers are completely muted, their journeys will continue. In another 16,700 years, Voyager 1 will pass our nearest neighboring star, Proxima Centauri, followed 3,600 years later by Voyager 2. Then they will continue to circle the galaxy for millions of years. They will still be out there, more or less intact, eons after our sun has collapsed and the heliosphere is no more, not to mention one Pale Blue Dot. At some point in their travels, they may manage to convey a final message. It won't be transmitted by radio, and if it's received, the recipients won't be human.

The message is carried on another kind of vintage technology: two records. Not your standard plastic version, though. These are made of copper, coated with gold and sealed in an aluminum cover. Encoded in the grooves of the Golden Records, as they are called, are images and sounds meant to give some sense of the world the Voyagers came from. There are pictures of children, dolphins, dancers and sunsets; the sounds of crickets, falling rain and a mother kissing her child; and 90 minutes of music, including Bach's Brandenburg Concerto No. 2 and Chuck Berry's "Johnny B. Goode."

And there is a message from Jimmy Carter, who was the U.S. president when the Voyagers were launched. "We cast this message into the cosmos," it reads in part. "We hope someday, having solved the problems we face, to join a community of galactic civilizations. This record represents our hope and our determination, and our good will in a vast and awesome universe." SA

Tim Folger is a freelance journalist who writes for *National Geographic, Discover,* and other national publications.

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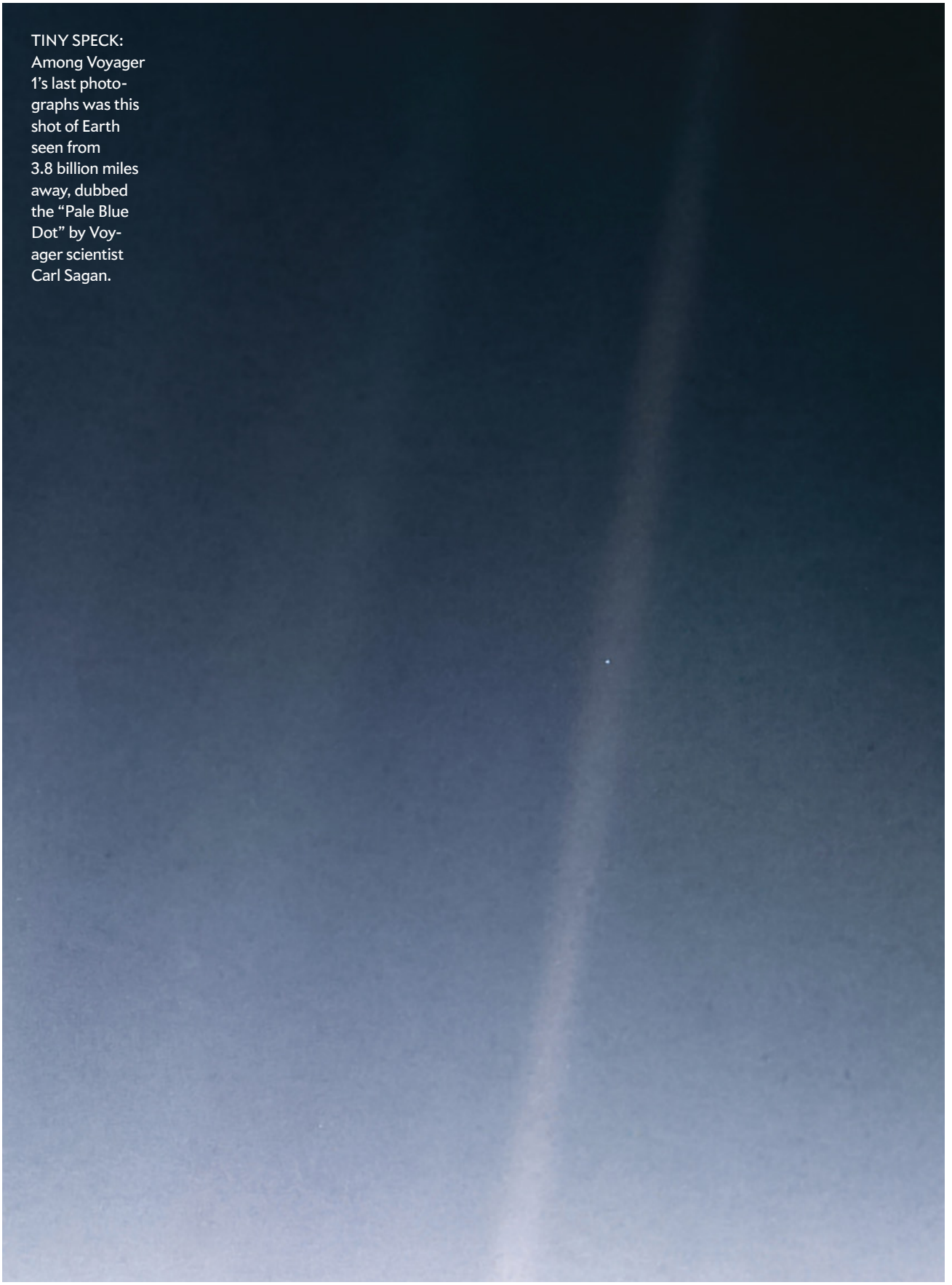

TINY SPECK: Among Voyager 1's last photographs was this shot of Earth seen from 3.8 billion miles away, dubbed the "Pale Blue Dot" by Voyager scientist Carl Sagan.

NASA/JPL-Caltech

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Portrait of a Black Hole

The first image of the behemoth at the center of the Milky Way opens new possibilities for understanding the nature of black holes

By Seth Fletcher

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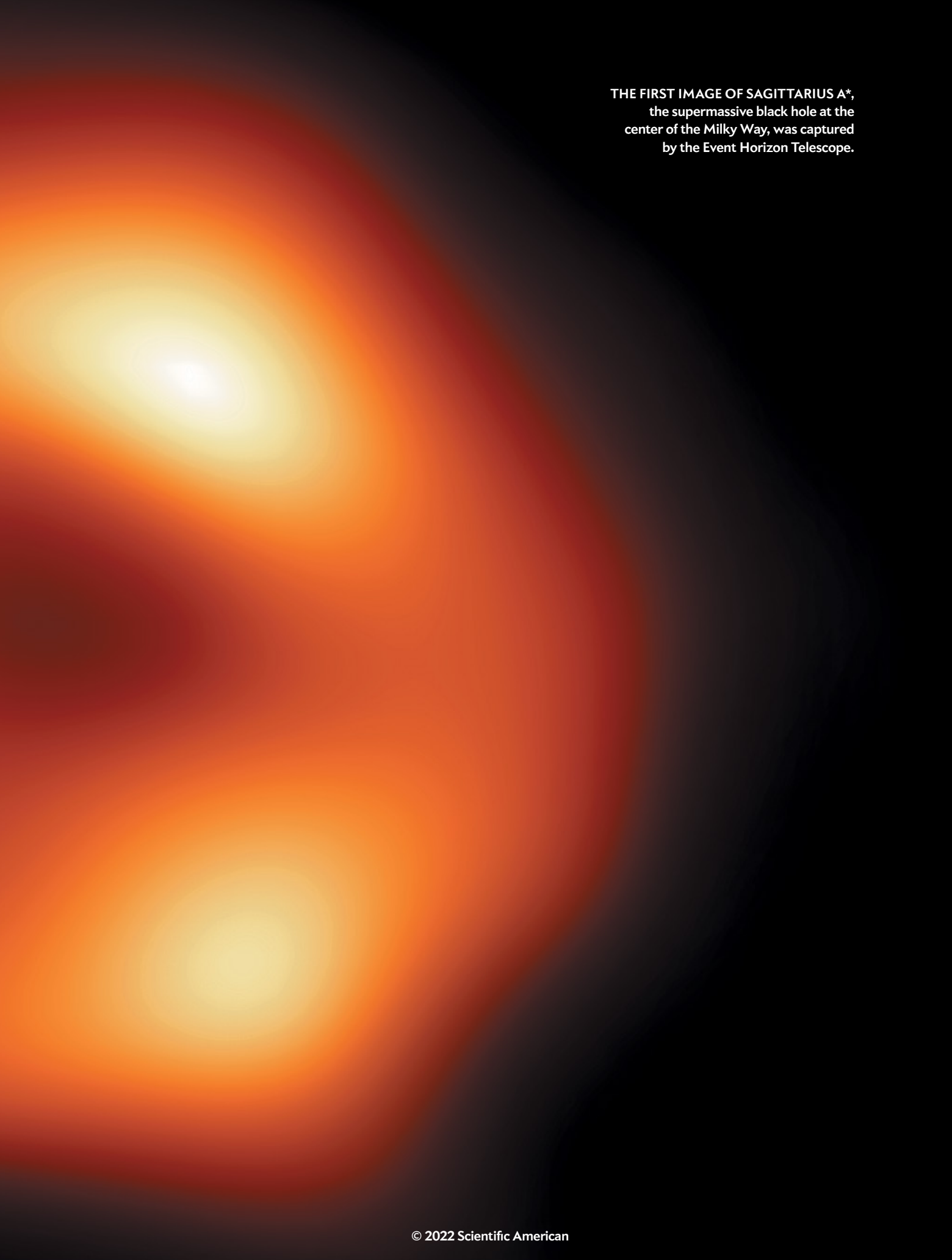

THE FIRST IMAGE OF SAGITTARIUS A*, the supermassive black hole at the center of the Milky Way, was captured by the Event Horizon Telescope.

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DEEP IN THE HEART OF THE MILKY WAY, STRANGE THINGS HAPPEN. THIS is a place where stars slingshot around apparently empty space at an appreciable fraction of the speed of light. Scientists have long thought that only a supermassive black hole could explain the stars' movements, but until this year, they hesitated to say that outright. For example, when astronomers Reinhard Genzel and Andrea Ghez shared a portion of the 2020 Nobel Prize in Physics, their citation specified that they were awarded for "the discovery of a supermassive compact object at the centre of our galaxy," not the revelation of a "black hole." The object is known as Sagittarius A* ("Sagittarius A star").

This past spring, however, the astronomers behind the Event Horizon Telescope (EHT) settled the matter by unveiling the first image of a supermassive black hole at the center of the Milky Way. It wasn't the first picture of a black hole this collaboration had captured—that was the iconic image of M87*, which they revealed in April 2019. But it was the one they wanted most. Sagittarius A* is our own private supermassive black hole, the still point around which our galaxy revolves.

Black holes trap everything that falls in, including light, so they are, in a very real sense, unseeable. But they warp spacetime around them so severely that, when they are illuminated by glowing streams of infalling matter shredded in their gravitational grip, they cast a "shadow." The shadow is about two and a half times larger than a black hole's event horizon, the boundary in spacetime through which nothing that passes can ever return.

The EHT captured images of this shadow using a technique called very long baseline interferometry (VLBI), which combines radio observatories on multiple continents to form a virtual Earth-size telescope, an instrument with the highest resolution in all of astronomy. In April 2017 the EHT collaboration spent several nights pointing that virtual instrument at Sagittarius A* and other supermassive black holes. The scientists then spent years analyzing the raw data and converting them into an image.

Part of the reason it took so long was the global devastation of the COVID pandemic. But the bigger challenge was that Sagittarius A* is constantly changing. The observatory's previous target, M87*, the black hole at the heart of the galaxy Messier 87 (M87), is so huge that the matter swirling around it takes many hours to complete a full orbit. Practically speaking, that means you can stare at it for a long time, and it will scarcely change. Sagittarius A* is more than 1,000 times less massive, so its appearance changes about 1,000 times faster, as matter moves in tighter, quicker orbits around the black hole. Katie Bouman, a California Institute of Technology computer scientist and astronomer who co-leads the EHT's imaging working group, said that matter orbits Sagittarius A* so quickly that it changes "minute to minute." Imagine taking a time-lapse photograph of a speeding bullet—it's not easy.

If Sagittarius A*'s mercurial nature made it hard to see, it also makes it an ideal laboratory for understanding black holes and Einstein's general theory of relativity, his hallowed theory of gravity. Through decades of study with all manner of telescopes, astronomers already knew Sagittarius A*'s basic measurements (its mass, diameter and distance from Earth) to great accuracy. Now, at last, they've gained the ability to watch it evolve—to watch as it feeds on flaring, flashing streams of matter—in real time.

SCIENTISTS STARTED TO SUSPECT THAT A BLACK hole lurked in the heart of the Milky Way in the early 1960s, not long after the discovery of active galactic nuclei—extremely bright regions at the cores of some faraway galaxies illuminated by voraciously feeding supermassive black holes. From our perspective here on Earth, active galactic nuclei are a thing of the past—we see them only in the distant, ancient universe. Where did they all go? In 1969 English astro-

EHT Collaboration (*preceding pages*)

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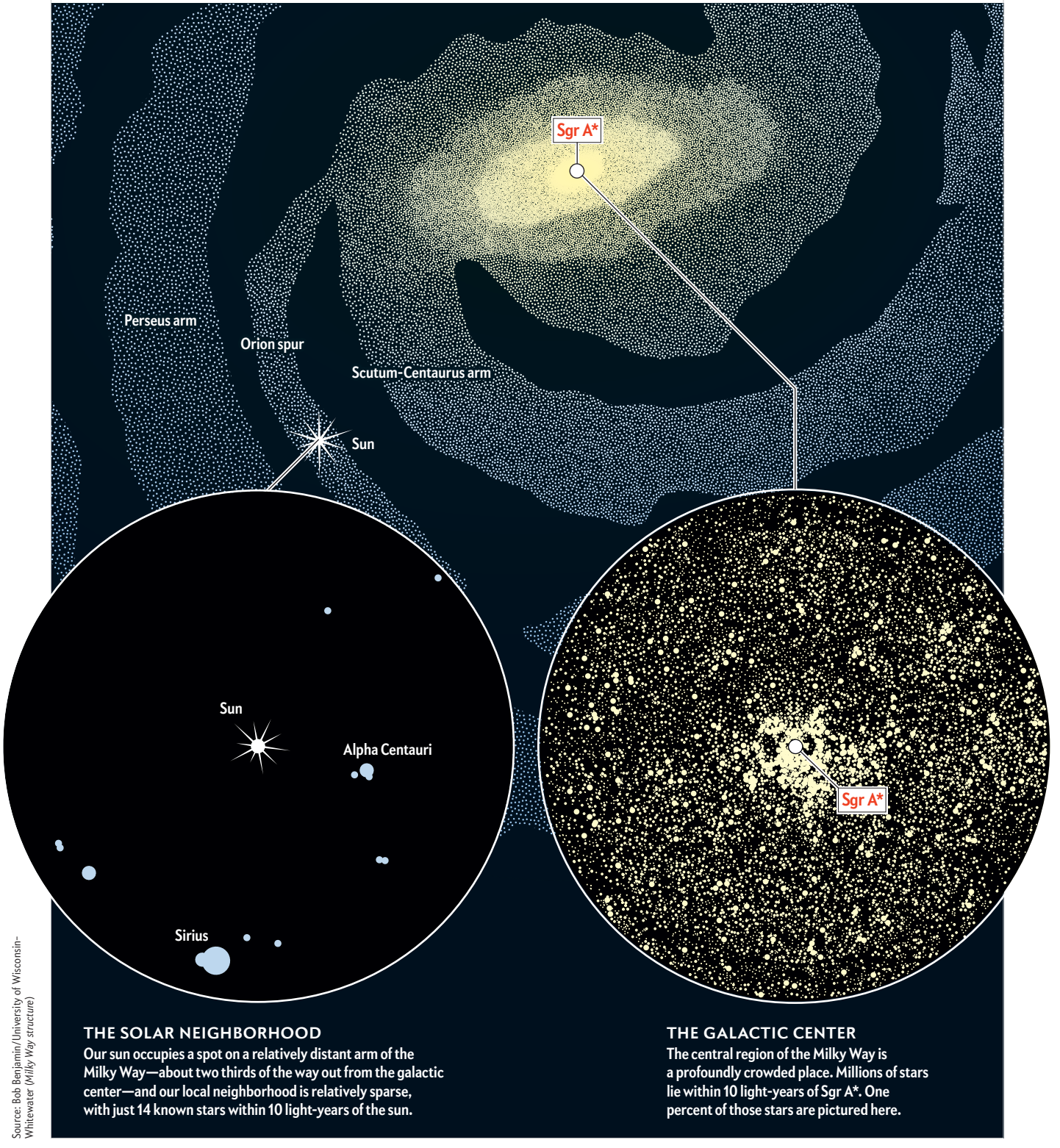
Our Black Hole

The Milky Way's central supermassive black hole, Sagittarius A*, is roughly 27,000 light-years from Earth, at the core of the dense, chaotic region known as the galactic center. With a diameter roughly equivalent to the planet Mercury's orbit around our own sun, it's not exactly small, but it's so far away that to us, it appears to be the size of a doughnut on the moon.



THE SOLAR NEIGHBORHOOD

Our sun occupies a spot on a relatively distant arm of the Milky Way—about two thirds of the way out from the galactic center—and our local neighborhood is relatively sparse, with just 14 known stars within 10 light-years of the sun.

THE GALACTIC CENTER

The central region of the Milky Way is a profoundly crowded place. Millions of stars lie within 10 light-years of Sgr A*. One percent of those stars are pictured here.

Source: Bob Benjamin/University of Wisconsin–Whitewater (*Milky Way structure*)

Graphic by Katie Peek

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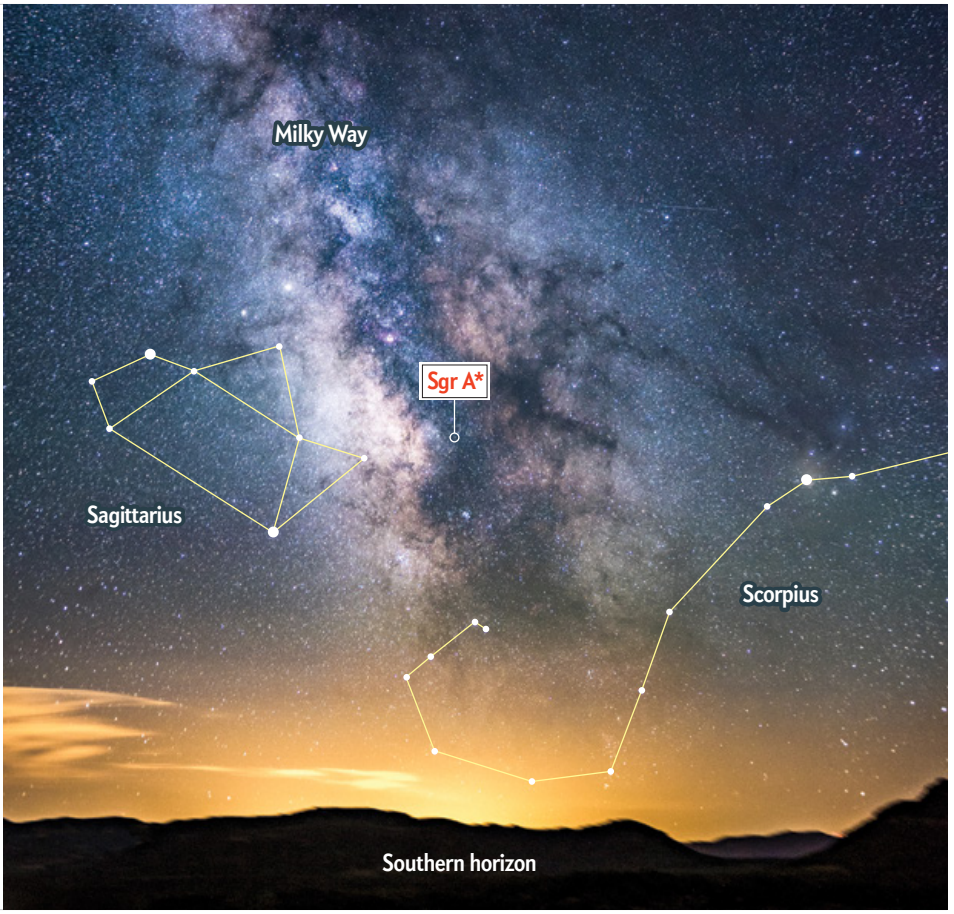
The Center of Our Galaxy

Sagittarius A* and the greater galactic center reside near the constellation Sagittarius. One of the major challenges the Event Horizon Telescope has faced is finding times when Sagittarius A* is "up"—above Earth's horizon—for all the observatories in the worldwide array, which are spread across continents and are located in both hemispheres.



physicist Donald Lynden-Bell argued that they didn't go anywhere. Instead, he said, they just went to sleep. Dormant supermassive black holes, he predicted, are slumbering all around us in the hearts of nearly all spiral galaxies, including our own.

In 1974 American astronomers Bruce Balick and Robert Brown pointed radio telescopes in Green Bank, W.Va., at the center of the Milky Way and discovered a dim speck they suspected was our galaxy's central black hole. They found it in a slice of sky, known as Sagittarius A, within the constellation Sagittarius. Radiation from the new source was lighting up—or "exciting"—surrounding clouds of hydrogen. Brown borrowed from the nomenclature of atomic physics, in which excited atoms are marked with an asterisk, and named the newfound speck Sagittarius A*.

For the next two decades radio astronomers kept gradually improving their view of Sagittarius A*, but they were limited by a lack of suitable telescopes, relatively clunky technology (think reel-to-reel magnetic tape) and the inherent difficulty of looking into the crowded galactic center.

Sagittarius A* is concealed by a multilayered veil. The first layer is the galactic plane—27,000 light-years' worth of stars, gas and dust that blocks visible light. Radio waves sail through the galactic plane unimpeded, but they're obscured by the veil's second layer—the scattering screen, a turbulent patch of space where density variations in the interstellar medium knock radio waves slightly off course. The final layer concealing Sagittarius A* is the infalling matter surrounding the black hole itself. Peering through that barrier is a bit like peeling off an onion's skins. The outer layers of matter emit longer-wavelength light—the same wavelengths VLBI traditionally works with. Making VLBI work with shorter-wavelength light would enable closer-in views approaching the black hole's event horizon, but it was a major technological challenge.

For a while, astronomers using other techniques besides VLBI had more success, steadily gathering indirect evidence that Sagittarius A*'s "speck" was actually a seething supermassive black hole. In the 1980s physicist Charles Townes and his colleagues showed that gas clouds in the galactic center were moving in ways that made sense only if they were under the influence of some great, unseen gravitating mass. And in the 1990s Ghez and Genzel independently began tracking the orbits of giant blue stars in the galactic center, mapping their motion around a heavy but hidden pivot point.

Meanwhile the situation for radio astronomers improved. In the late 1990s and early 2000s a new gen-

Eloi Omella/Getty Images (*Milky Way photograph*)

Graphic by Katie Peek

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eration of short-wavelength radio telescopes started to come online—telescopes that, if augmented with lots of bespoke equipment, could participate in VLBI observations at the microwave frequencies thought to shine from the edge of Sagittarius A*'s shadow. At the same time, the computing revolution that led to solid-state hard drives and smartphones in every pocket vastly increased the amount of data that each observatory in a network of radio telescopes could record and process.

In 2007 a small precursor to the EHT took advantage of these trends and used a trio of telescopes in Hawaii, California and Arizona to pierce the veil surrounding Sagittarius A*. The result was far from an image, but the project saw *something*—presumably, light from the long-sought shadow.

The first prediction of black hole shadows came in 1973, when physicist James Bardeen showed that a black hole in front of a bright background would produce a silhouette. He decided that "there seems to be no hope of observing this effect." In 2000, however, astrophysicists Heino Falcke, Fulvio Melia and Eric Agol demonstrated that a microwave-gathering, Earth-size radio telescope should be able to see the shadow of Sagittarius A*.

Half a decade afterward, a few dozen of the astronomers and astrophysicists laboring in this obscure corner of astronomy agreed on the formal goal of building a virtual planet-scale radio telescope to observe that shadow. The first official kickoff meeting for the project occurred in January 2012, and the Event Horizon Telescope was born.

Five years later, after growing into a collaboration of more than 200 scientists with eight participating observatories across the globe, the EHT took its first realistic shot at seeing the shadow of Sagittarius A*. Over the course of 10 days in April 2017, telescopes in North America, South America, Hawaii, Europe and Antarctica collectively zoomed in on the galactic center and other black holes, gathering 65 hours of data on 1,024 eight-terabyte hard drives, which were shipped to supercomputer banks in Massachusetts and Germany for correlation. Five years after *that,* the elated EHT researchers showed the world that their experiment worked.

THE DAY THE EHT COLLABORATION REVEALED Sagittarius A*'s image, the *Astrophysical Journal Letters* published a special issue devoted to the new results. In six technical papers, the scientists presented a multidimensional portrait of our black hole.

The EHT image confirmed the basics. We've long known that Sagittarius A* is about 27,000 light-years away. Years spent tracking the orbits of stars around Sagittarius A* with infrared telescopes had already given astronomers an accurate measure of the black hole's mass—the equivalent of roughly four million suns. Plug those two numbers (distance and mass) into equations derived from general relativity, and you can calculate the expected size of the black hole's shadow. Sure enough, the image matches the prediction. The shadow has a diameter of 52 micro arc seconds, which means that to us here on Earth it is, in the astronomers' formulation, the size of a "doughnut on the moon." After seeing the shadows of both Sagittarius A* and M87*—black holes that differ in mass by three orders of magnitude—the scientists concluded that the phenomena are "universal features of black holes."

The EHT observations, combined with simultaneous monitoring by the Chandra and Nu-STAR x-ray telescopes and other instruments, are starting to settle long-standing questions about Sagittarius A*'s environment. By measuring the spectra of light shining from the object—that is, the light broken up into its constituent frequencies—astronomers long ago determined that the matter orbiting the black hole is a diffuse gas of electrons and protons. We now have a much better idea of where that matter comes from. Observations from the Chandra x-ray telescope show that the black hole pulls that matter from the atmospheres of stars orbiting it. Not that it pulls very much. Sagittarius A* is on a starvation diet—less than 1 percent of the stuff captured by the black hole's gravity ever makes it to the event horizon. That explains why the black hole is so dim. Despite being four million times more massive than our sun, Sagittarius A* is only 100 times brighter.

It wasn't always so faint. It appears that as recently as 60 or 70 years ago, Sagittarius A* went on a feeding binge, a burst of activity that left "light echoes"—light bouncing off nearby clouds of dust and gas—that astronomers have detected using x-ray telescopes. And it still has its active moments. On April 11, 2017, Sagittarius A* emitted a bright x-ray flare. The cause, most likely, was the twisting and recombining of magnetic fields inside the matter orbiting the black hole—the same basic dynamic that causes solar flares in our own star. Directly observing these flares is a major goal for future campaigns.

There's much more to learn about Sagittarius A*. For example, the EHT observations show that, like everything else in space, the black hole is spinning—but we don't know how fast. Future observations also aim to show exactly how the black hole eats infalling matter and, with luck, make movies of the black hole evolving over time.

The first EHT picture of Sagittarius A* is just the beginning, but it does tell us what the object is not. The presence of a distinctive shadow means Sagittarius A* has an event horizon—the defining feature of a black hole. That means we finally know it's not a really, really, really dense star, or a wormhole, or a naked singularity (a point of infinite density unconcealed by an event horizon), or any of the other exotic oddities theorists have proposed over the years. It's nothing stranger than a supermassive black hole—still a pretty strange thing indeed—now brought within view, closer to revealing its secrets. SA

Seth Fletcher is chief features editor at *Scientific American.* His book *Einstein's Shadow* (Ecco, 2018) is about the Event Horizon Telescope and the quest to take the first picture of a black hole.

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BREAKING COSMOLOGY

JWST's first images include unimaginably distant galaxies that challenge theories of how quickly these structures can form

By Jonathan O'Callaghan

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GALAXIES from the depths of cosmic time appear in a small crop from "deep field" observations taken by the James Webb Space Telescope (JWST). The most distant objects in such images may reveal surprising new details about the early universe.

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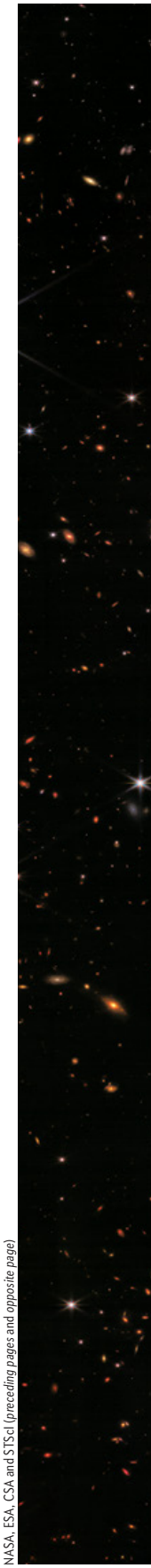

NASA, ESA, CSA and STScI (*preceding pages and opposite page*)

ROHAN NAIDU WAS AT HOME WITH HIS GIRLFRIEND WHEN HE found the galaxy that nearly broke cosmology. As his algorithm dug through early images from the James Webb Space Telescope (JWST) late one night this past July, Naidu shot to attention. It had sifted out an object that Naidu recognized was inexplicably massive and dated back to just 300 million years after the big bang, making it older than any galaxy ever seen before. "I called my girlfriend over right away," Naidu says. "I told her, 'This might be the most distant starlight we've ever seen.'" After exchanging excited messages with one of his collaborators "with lots of exclamation marks," Naidu got to work. Days later they published a paper on the candidate galaxy, which they dubbed "GLASS-z13." The Internet exploded. "It reverberated around the world," Naidu says.

The discovery of this galaxy, just weeks into JWST's full operations, was beyond astronomers' wildest dreams. JWST—the largest, most powerful observatory ever launched from Earth—was built to revolutionize our understanding of the universe. Stationed 1.5 million kilometers away from earthly interference and chilled close to absolute zero by its tennis court–sized sunshade, the telescope's giant segmented mirror and exquisitely sensitive instruments were designed to uncover details of cosmic dawn never before observed.

This is the scarcely probed era—no more than a few hundred million years after the big bang itself—in which the very first stars and galaxies coalesced. How exactly this process unfolded depends on exotic physics, ranging from the uncertain influences of dark matter and dark energy to the poorly understood feedbacks between starlight, gas and dust. By glimpsing galaxies from cosmic dawn with JWST, cosmologists can test their knowledge of all these underlying phenomena—either confirming the validity of their best consensus models or revealing gaps in understanding that could herald profound new discoveries.

Such observations were supposed to take time; initial projections estimated the first galaxies would be so small and faint that JWST would find at best a few intriguingly remote candidates in its pilot investigations. Things didn't quite go as planned. Instead, as soon as the telescope's scientists released its very first images of the distant universe, astronomers such as Naidu (at the Massachusetts Institute of Technology) started finding numerous galaxies within them that, in apparent age, size and luminosity, surpassed all predictions. The competition for discovery was fierce: with each new day, it seemed, claims of yet

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THE INTERACTING galaxies of Stephan's Quintet, as seen by JWST, approximately 290 million light-years away from Earth. Covering one fifth of the moon's diameter, this mosaic is constructed from almost 1,000 separate images and reveals never-before-seen details of this galaxy group.

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another record-breaking "earliest-known galaxy" emerged from one research group or another. "Everyone was freaking out," says Charlotte Mason, an astrophysicist at the University of Copenhagen. "We really weren't expecting this."

In the weeks and months following JWST's findings of surprisingly mature "early" galaxies, theorists and observers have been scrambling to explain them. Could the bevy of anomalously big and bright early galaxies be illusory, perhaps because of flaws in analysis of the telescope's initial observations? If genuine, could they somehow be explained by standard cosmological models? Or, just maybe, were they the first hints that the universe is more strange and complex than even our boldest theories had supposed?

At stake is nothing less than our very understanding of how the orderly universe we know emerged from primordial chaos. JWST's early revelations could rewrite the opening chapters of cosmic history, which concern not only distant epochs and faraway galaxies but also our own existence here in the familiar Milky Way. "You build these machines not to confirm the paradigm but to break it," says JWST scientist Mark McCaughrean, a

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AN IMAGE FROM JWST reveals hundreds of previously invisible newborn stars in the stellar nursery known as the Carina Nebula, a vast agglomeration of gas and dust some 7,600 light-years from Earth.

senior adviser for science and exploration at the European Space Agency. "You just don't know how it will break."

DEEP LOOKS FOR COSMIC DAWN

ONE MIGHT SAY JWST'S observations of early galaxies have been billions of years in the making, but more modestly they trace back to the Space Telescope Science Institute (STScI) in 1985. At the time the Hubble Space Telescope was still five years away from launching on a space shuttle. But Garth Illingworth, then deputy director of the STScI, was surprised one day when his boss, then director Riccardo Giacconi, who died in 2018, asked him to start thinking about what would come after Hubble much farther down the road. "I protested, saying we've got more than enough to do on Hubble," Illingworth recalls. But Giacconi was insistent: "Trust me, it'll take a long time," he

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said. So, Illingworth and a handful of others got to work, drawing up concept ideas for what became known as the Next Generation Space Telescope (NGST), later renamed to JWST after a former NASA administrator.

Hubble would be transformational, but astronomers knew its capabilities would be limited by its observations in visible light. As light from a very distant galaxy travels across the cosmic abyss, it is stretched by the expansion of the universe—a broadening of wavelengths known as redshift. The higher the redshift value, the more stretching the light has experienced, and thus the more distant its source galaxy. Redshifts for early galaxies are so high that their emitted visible light has stretched into infrared by the time it arrives at our telescopes, which is why Hubble could not see them. The NGST, for comparison, would observe in infrared and would boast a very large (and very cold) starlight-gathering mirror, allowing it to peer much deeper into the universe. "Everybody realized that Webb would be the telescope for looking at early galaxies," Illingworth says. "That became the primary science goal."

The need for the telescope was highlighted in December 1995, when astronomers pointed Hubble at a seemingly empty patch of the sky for 10 consecutive days. Many experts predicted the extended observation would be a waste of resources, revealing at best a handful of dim galaxies, but instead the effort was richly rewarded. The resulting image, the Hubble Deep Field, showed the "empty" spot was filled with galaxies by the thousands, stretching back 12 billion years into the 13.8-billion-year history of our universe. "There were galaxies everywhere," says Illingworth, now an astrophysicist at the University of California, Santa Cruz. The Hubble Deep Field showed that the early universe was even more crowded and exciting than most anyone had expected, offering observational treasures to those who took the time and care to properly look. Yet, impressive as Hubble's Deep Field was, astronomers wanted more.

After more than two decades of labor at a cost of some $10 billion, JWST finally launched on Christmas Day 2021. The telescope reached its deep-space destination a month later, where it would endure exhaustive testing to ensure its optimal performance. By July 2022 it was ready to begin its long-awaited first year of science observations, known as Cycle 1. Part of the telescope's early time was devoted to high-impact programs across a range of disciplines from which data would immediately be made public. Two of those, CEERS (the Cosmic Evolution Early Release Science Survey) and GLASS (the Grism Lens–Amplified Survey from Space), independently spent dozens of hours looking for galaxies in the early universe by staring at separate small portions of the sky. Not much was expected—perhaps a slightly more ornate version of the Hubble Deep Field but nothing more. Steven Finkelstein of the University of Texas at Austin, the lead on CEERS, says extremely distant galaxies were predicted to pop up only "after a few cycles of data" from multiple programs.

Instead, much to the surprise of astronomers, extremely distant galaxies came into view immediately. Hubble's record for the most distant known galaxy had been GN-z11, spotted in 2015 at a redshift of 11 thanks to a 2009 upgrade that enhanced the telescope's modest infrared capabilities. A redshift of 11 corresponds to a cosmic age of about 400 million years, a point at the brink of when galaxy formation was thought to begin. But

NASA, ESA, CSA and STScI

from the very first GLASS data, two teams—one led by Naidu in that breathless late-night discovery—independently found GLASS-z13 at a redshift of 13, some 70 million years farther back in time.

In their quest for quick results, the researchers relied on redshift estimates derived from simple brightness-based measurements. These are easier to obtain but less precise than direct measurements of redshift, which require more dedicated observation time. Nevertheless, the simplified technique can be accurate, and here it suggested a galaxy that was unexpectedly bright and big, already bearing a mass of stars equivalent to a billion suns, just a few hundred times less than that of the Milky Way's stellar population, despite our own galaxy being billions of years more mature. "This was beyond our most optimistic expectations," says Tommaso Treu, an astronomer at the University of California, Los Angeles, and the lead on GLASS.

The record didn't last long. In the following days, dozens of galaxy candidates from CEERS and GLASS sprang into view with estimated redshifts as high as 20—just 180 million years after the big bang—some with disklike structures that were not expected to manifest so early in cosmic history. Another team, meanwhile, found evidence for galaxies the size of our Milky Way at a redshift of 10, less than 500 million years after the big bang.

Such behemoths emerging so rapidly defies expectations set by cosmologists' standard model of the universe's evolution. Called Lambda CDM (LCDM), this model incorporates scientists' best estimates for the properties of dark energy and dark matter, which collectively act to dominate the emergence of large-scale cosmic structures. ("Lambda" refers to dark energy, and "CDM" refers to dark matter that is relatively sluggish, or "cold.") "Even if you took everything that was available to form

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A SIDE-BY-SIDE COMPARISON shows JWST's remarkably detailed observations of the Southern Ring Nebula in near-infrared light (*left*) and mid-infrared light (*right*). Located more than 2,000 light-years from Earth, the nebula is composed of shells of gas and dust expelled from a dying star, which in each image can be seen near the nebula's core.

stars and snapped your fingers instantaneously, you still wouldn't be able to get that big that early," says Michael Boylan-Kolchin, a cosmologist at the University of Texas at Austin. "It would be a real revolution."

HOW TO BUILD A GALAXY

TO UNDERSTAND THE DILEMMA, a brief refresher is needed. In the first second after the big bang, our universe was an almost inconceivably hot and dense soup of primordial particles. Over the next three minutes, as the cosmos expanded and cooled, the nuclei of helium and other very light elements began to form. Fast-forward 400,000 years, and the universe was cold enough for the first atoms to appear. When the universe was about 100 million years old, theorists say, conditions were finally right for the emergence of the first stars. These giant fireballs of mostly hydrogen and helium were uncontaminated by heavier elements found in modern-day stars, so they possessed significantly different properties. Larger and brighter than today's stars, these first suns coalesced in protogalaxies—clusters of gas that clung to vast, invisible scaffolds of dark matter. Gravity guided the subsequent interactions between these protogalaxies, which eventually merged to form larger galaxies. This process of becoming, of the early universe's chaos giving way to the more orderly cosmos we know today, is thought to have taken about a billion years.

JWST's discovery of bright galaxies in the early cosmos challenges this model. "We should see lots of these little protogalactic fragments that have not yet merged to make a big galaxy," says Stacy McGaugh, a cosmologist at Case Western Reserve University. "Instead, we're seeing a few things that are already big galaxies." Some of these galaxies may be impostors, much closer galaxies shrouded in dust that makes them look dimmer and farther away when brightness-based measurements are used. Follow-up observations of GLASS-z13 in August by the Atacama Large Millimeter Array (ALMA) in Chile, however, suggest that is not the case for this candidate, because ALMA did not see evidence for large amounts of dust. "I think we can exclude low-redshift interlopers," says Tom Bakx, an astronomer at Nagoya University in Japan, who led the observations. Yet the lack of dust means ALMA struggled to see the galaxy at all, showing how difficult it could be for telescopes to confirm observations made using JWST's advanced capabilities. "The good news is there's nothing detected," Naidu says. "The bad news is there's nothing detected." Only JWST, in this case, can follow up itself.

The most startling explanation is that the canonical LCDM cosmological model is wrong and requires revision. "These results are very surprising and hard to get in our standard model of cosmology," Boylan-Kolchin says. "And it's probably not a small change. We'd have to go back to the drawing board." One controversial idea is modified Newtonian dynamics (MOND), which posits that dark matter does not exist and that its effects can instead be explained by large-scale fluctuations in gravity. To date, JWST's observations could support such a theory. "MOND has had a lot of its predictions come true—this is another one of them," says McGaugh, who is one of the idea's leading proponents. Others remain unconvinced. "So far everything that we've tried to test MOND hasn't been able to really provide a satisfactory answer," says Jeyhan Kartaltepe, an astrophysicist at the Rochester Institute of Technology.

One simpler solution is that galaxies in the early universe could have little or no dust, making them appear brighter. This scenario could confound efforts to calculate the galaxies' true masses and could perhaps also explain ALMA's difficulty spotting GLASS-z13. "It could be that supernovae didn't have enough time to produce the dust, or maybe in the initial phases [of galaxy formation] the dust is expelled from galaxies," says Andrea Ferrara, an astronomer at the Scuola Normale Superiore in Italy, who has proposed such a possibility. Alternatively, Mason and her colleagues suggest that in its observations of the early universe JWST may so far be seeing only the very brightest young galaxies, as they should be the easiest to spot. "Maybe there's something happening in the early universe that means it's easier for some galaxies to form stars," she says.

David Spergel, a theoretical astrophysicist and current president of the Simons Foundation in New York City, agrees. "I think what we're seeing is that high-mass star formation is very efficient in the early universe," he says. "The gas pressures are higher. The temperatures are higher. That has an enormous impact on the environment for star formation." Magnetic fields might have arisen earlier in the universe than we thought, driving material to kick-start the birth of stars. "We might be seeing a signature of magnetic fields emerging very early in the universe's history," Spergel says.

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A RUSH TO BREAK THE UNIVERSE

THE RAPID FLOW of scientific papers from JWST's initial observations is no fluke; when the first data started streaming down, astronomers were eagerly waiting. "People had been working on their pipelines for years," Boylan-Kolchin says. Instead of the traditional peer-review processes, which can take months, astronomers published on arXiv, a website where scientific papers can be uploaded after minimal review by moderators but well before formal peer review. This new form of peer review is unfolding in near real time on Twitter and other social media platforms. "It's science by arXiv," Naidu says. The resulting frenzy was intense—and surprising. "I expected a lot of activity," says Nancy Levenson, STScI's interim director. "But I underestimated the amount."

The result was that scientific results could be rapidly publicized and discussed, but some fear at a cost. "People were rushing things a little bit," says Klaus Pontoppidan, JWST's project scientist at STScI. "The gold standard is a refereed, peer-reviewed paper." Early calibration issues with JWST, for example, may have affected some results. Nathan Adams at the University of Manchester in England and his colleagues found there could be dramatic changes, with one galaxy at a redshift of 20.4 recalibrated to a redshift of just 0.7. "We need to calm down a little bit," Adams says. "It's a bit too early to say we've completely broken the universe."

Such issues are unlikely to eradicate all of JWST's high-redshift galaxies, however, given their sheer number. "It's more likely that the early universe is different from what we predicted," Finkelstein says. "The odds are small that we're all wrong." Astronomers are now racing to conduct follow-up observations with JWST. Levenson says she's currently reviewing about a dozen proposals from various groups asking for additional JWST observing time, most of which are seeking to scrutinize high-redshift galaxy candidates. "Considering the excitement and importance of these early discoveries, we thought it was appropriate to ask for a little bit of time to confirm them," says Treu, who put forward one of the proposals.

More upcoming programs are set to hunt for distant galaxies, such as COSMOS-Webb, led by Kartaltepe, which is expected to hugely increase the known population of early galaxies by observing a wider swath of sky for hundreds of hours. "We estimate there are thousands we'll be able to detect," she says. Future proposals might look for evidence of those first protogalaxies, perhaps using the explosive deaths of supersized first stars in especially luminous and energetic supernovae as markers for their existence. Some estimates suggest JWST could see as far as a redshift of 26, just 120 million years after the big bang, a cosmic blink of an eye. Much other work will be done to follow up the growing list of high-redshift candidates. "Even confirming a handful of these would be quite amazing," Naidu says. "It would demonstrate we're not getting fooled."

JWST has ushered in a new era of science, and despite the uncertainties, the rapid communication of new discoveries has invigorated astronomers. "It's been fantastic," Treu says. "It's really wonderful to see the community so engaged and excited." Now the question is, if we can truly believe what we are seeing, is it time to reappraise our understanding of the dawn of time? "We're peering into the unknown," Mason says. SA

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THE CARTWHEEL GALAXY displays its characteristic dust-rich "spokes" and starry inner and outer rings in this near-infrared view from JWST. These features ripple like shock waves from the galaxy's center, the site of a high-speed collision with another galaxy some 400 million years ago.

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ASTROPHYSICIST Ekta Patel, a postdoctoral fellow at the University of California, Berkeley, studies satellite galaxies around the Milky Way and Andromeda.

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WOMEN TAKE ON THE STARS

A new wave of astronomers are leading a revolution in scientific culture

By Ann Finkbeiner

Photograph by Timothy Archibald

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SOME YEARS AGO I MADE UP A LIST OF THINGS I WAS TIRED of reading in profiles of women scientists: how she was the first woman to be hired, say, or to lead a group or to win some important prize. I had just been assigned a profile of a splendid woman astronomer, and her "firsts" said nothing about the woman and everything about the culture of astronomy: a hierarchy in which the highest ranks have historically included only scientists who are male, white and protective of their prerogatives. My list evolved into the "Finkbeiner test," and to abide by it, I pretended we had suddenly leaped into a new world in which gender was irrelevant and could be ignored. I would treat the person I was interviewing like she was just an astronomer.

Later, working on another story, I started hearing about a cohort of young women astronomers who were the ones to call if I wanted to talk to the field's best. If the top of the scientific hierarchy now included large numbers of women, I wondered whether they might live in a post–Finkbeiner test world—that is, whether they were just astronomers, not "women astronomers." I turned out to be 180 degrees wrong. True, they are at the top, but they are outspokenly *women* astronomers, and they are remaking astronomy.

Earlier generations of women had worked against the restrictions of the hierarchical culture, but change was glacially gradual, partly because the women were few. With time, however, small changes in their numbers added up and then tipped over, creating a different world. This recent cohort of women, who earned doctoral degrees around 2010, wins prizes, fellowships and faculty positions; does not suffer foolishness; and goes outside the established rules to make its own. "We create the culture we want," says Heather Knutson, who won the Annie Jump Cannon Award in 2013. She is a full professor at the California Institute of Technology and studies the properties of exoplanets. "There are more of us now, and we have the power to shape it."

One of the rules of their world is that it includes not only women but also people who have been marginalized for other reasons, that is, people of color, disabled people, LGBTQ+ people and those who are nonbinary—people whose numbers in the field are still strikingly unrepresentative.

These women astronomers are scientifically and culturally ambitious, and they shine of their own light; they sparkle. Their world still has restrictions but not as many, and the women react to them more defiantly. "We don't want to change ourselves to fit the mold," says Ekta Patel, a Miller postdoctoral fellow at the University of California, Berkeley, who simulates the behavior of satellite galaxies. "I enjoy being a girl," says Lia Medeiros, a National Science Foundation postdoctoral fellow at the Institute for Advanced Study in Princeton, N.J., where she studies black holes. "And I'm going to be a girl all over their physics. This is my world, too."

WOMEN HAVE BEEN ASTRONOMERS since forever, but they have needed to be made of iron. Vera C. Rubin, who got her Ph.D. in 1954, was advised in school to stay away from science. She kept going anyway by telling herself she was just different from other people. She did her graduate studies where her husband's job took them, raised children and then got a position where she was the only woman. She discovered the first solid evidence of the dark matter that, years later, is still one of cosmology's biggest mysteries. She was elected to the National Academy of Sciences (NAS), won the National Medal of Science and, after she died in 2016, had an ambitious observatory named after her; one of its missions is to map dark matter.

Back in 1965, Rubin confronted the Hale Telescope's no-women-allowed rule, ostensibly imposed because observing is an all-night process and the observatory had no ladies' room. Rubin cut a piece of paper into the shape of a woman with a skirt and pasted it on a bathroom door, creating the Hale's first ladies' room.

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SARAH HÖRST, a planetary scientist at Johns Hopkins University, studies atmospheric chemistry.

Rubin was extraordinary, but her work conditions were dead standard. All women astronomers in her world—those earning doctorates between the mid-1950s and the mid-1980s—had the same stories, which disconcertingly often mention bathrooms. The women were not admitted, were not allowed, built careers around their families, developed thick shells impervious to aggression and were almost completely isolated. Their best bet was to blend in with the male culture of astronomy. Margaret Burbidge—Ph.D. 1943, co-discoverer of the formation of the universe's chemical elements, awarded the National Medal of Science and elected to the NAS—refused the women-only Annie Jump Cannon Award because she thought women should be discriminated neither against nor for. A woman astronomer in Rubin's world was so alone as to be virtually *sui generis*—one of the few of her kind. Meg Urry, Israel Munson professor of physics and astronomy at Yale University, says that for her, Rubin was an "existence-proof."

But in the 1960s and 1970s a series of court decisions, affirmative-action policies, laws and executive orders mandated that universities no longer exclude women and minorities for either study or employment. By the time Urry got her Ph.D. in 1984, some constraints on Rubin's world were illegal, and others were publicly deplored.

By 1987 Urry was working at the Space Telescope Science Institute (STScI) on active galactic nuclei, unusually bright objects accompanied by light-years-long jets. She found that a subset of these objects were the same creature, eventually shown to be a supermassive black hole embedded in a galaxy and sending out jets. STScI was then only six years old, and of the first 60 scientists it hired, 59 were men. In 1992 Urry organized a series of conferences, eventually run by the American Astronomical Society (AAS), on women in astronomy. That year's meeting was held in Baltimore. The resulting advisory, called the Baltimore Charter, pointed out that as long as women were in charge of familial life, their careers were going to look different from men's. It recommended, among other things, "swift and substantial action" against sexual harassers and implementation of the tenets of affirmative action—including, most radically, Urry says, that hir-

Photograph by Amanda Andrade-Rhodes

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UNIVERSITY OF WASHINGTON'S astronomy department includes (*from left*) Jessica Werk, Emily Levesque and Sarah Tuttle.

ing shortlists should include at least one woman. But the biggest impact of that first conference, Urry says, "was being in a room with 200 women astronomers. Before that you'd meet three women in the ladies' room, so this was a huge and shocking thing."

Demographic surveys of Urry's world—women who got their Ph.D.s roughly between 1985 and 2010—show that in the 1990s women were just under 15 percent of the astronomy postdocs and assistant and associate professors and around 5 percent of the full professors. Given their low numbers, women in this environment still thought it best to blend in with the established culture. "In Meg's world," says Nicolle Zellner, Ph.D. 2001, co-chair of the AAS's Committee on the Status of Women in Astronomy and a full professor at Albion College in Michigan, "women worked hard, fit in and hoped to be rewarded."

Over time the number of women slowly went up to almost enough. In 1999 women were about 16 percent of the assistant and associate professors of astronomy; in 2013 they were around 22 percent. In 1999 women were 7 percent of the full professors; in 2013 they were 14 percent. These changes in numbers, Urry says, drove changes in policy and practice.

Institutions and professional societies increasingly adopted the Baltimore Charter's ideas, including offering affordable child care and parental leave, adapting tenure deadlines to family circumstances and publishing codes of conduct. Prizes began to allow self-nomination, avoiding some of the bias of the nomination process.

Eventually women's increased numbers and reduced restrictions created widespread conditions for what I think of as sparkle. Sparkle is a fireworkslike quality, noticeable in talks and conversations, that in earlier generations of astronomers was most obvious in young men: visible brilliance, intensity, easy confidence and a springy joy. Quantifying sparkle is tricky. Most of its metrics—time on telescopes, named invited talks, citations for papers, leadership of teams—are hard to define and count precisely. But some examples illustrate the point. See, for instance, the fraction of prizes given to women by either the Kavli Foundation or the AAS for general scientific contributions: from 2001 to 2005 it was 4 percent; 2006 to 2010, 12 percent; 2011 to 2015, 23 percent; 2016 to 2021, 30 percent. Or the fraction of panel seats granted to women for the NAS's decadal surveys to decide the future course of astronomy: 1990, 8 percent; 2000, 15 percent; 2010, 27 percent; 2020, 43 percent. Or look at prestigious postdoctoral fellowships that award research money to be taken to whatever institution one chooses, including the Chandra, Sagan, Einstein and Hubble postdoctoral fellowships. From 1996 to 2010, between 24 and 28 percent went to women; 2011 to 2015, 31 percent; 2016 to 2021, 45 percent. In 2021, of the now merged Sagan Einstein Hubble fellowships, awarded by NASA, women won 58 percent.

Notably, somewhere around 2015 the lines charting all three metrics took a fast turn to the northeast. Moreover, women in this post-2015 subcohort are visibly "badasses," says Jessica Werk, Ph.D. 2010, a Hubble fellow and associate professor at the

Photograph by Annie Marie Musselman

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University of Washington who studies the gas in and around galaxies: "They *really* don't take people's shit."

CAITLIN CASEY, PH.D. 2010, was a Hubble fellow, won the AAS's Newton Lacy Pierce Prize and is now an associate professor at the University of Texas at Austin. She studies the lives of early massive galaxies, best observed at many wavelengths and in enormous surveys with teams of hundreds. She leads two teams: one surveying millions of galaxies using the major telescopes in space and on the ground; the other using the James Webb Space Telescope to look back to a billion years after the beginning of time for young galaxies.

When she was a postdoctoral researcher, Casey heard advice from senior scientists about navigating academia: "Work extra hard. Take telecons at 4 A.M. Put your head down until you're safe." She and her friends, also in junior positions, thought the advice was bad. They told one another, "That's a load of crap. Why don't we do our own thing and see if we get hired?" She was hired. As a new faculty member, she was again advised against activism before tenure. "I worried about that, but I decided to ignore it," she says. "I got tenure." Every time she gets similarly bad advice, she says, "I muster the presence of these other women."

The sparkly cohort knows that its backbone is based on the presence of other women. Sarah Tuttle, Ph.D. 2010, an assistant professor at the University of Washington, builds instruments to study nearby galaxies. "When there are three of us," she says, "we can spread out the work; there's more room to throw elbows." Laura Chomiuk, Ph.D. 2010, a Jansky fellow and associate professor at Michigan State University who studies novae, adds, "I do feel like I have allies. I can always find an ally." They either join networks or start their own. They have lunches, meet at conferences, buttonhole departmental women visitors, set up private Facebook pages and Slack channels, and are all over Twitter. "Every university I've been at has had a women's group," says Danielle Berg, Ph.D. 2013, an assistant professor at the University of Texas at Austin who studies the evolution of star-forming galaxies.

If you feel a group has your back, you are freer to be your own individual self. "I don't want to be a blank-faced robot astronomer," says Sinclaire Manning, Ph.D. 2021, a Hubble fellow at the University of Massachusetts Amherst who studies brilliant dusty young galaxies. "I can't not be a Black woman, and I would never hide that I am." Berg had purple hair and wore a bright green suit to a job interview, and, she says, "they decided that was a good thing." With backing, you are also free, like Casey's friends, to disagree with established culture. Sarah Hörst, Ph.D. 2011, an associate professor at Johns Hopkins University, studies atmospheres around planets and moons. She told me, "My first year here I thought, if I have to sit through this for seven more years [until tenure], what I will be at the end of it is not going to be someone who changes things. If I had to sit quietly during faculty meetings, I'd have quit."

Some of what they are not sitting quietly through is astronomy's traditionally sexist, aggressive culture—people on committees saying things like, "Sure, she's pretty enough to hire," remembers Laura Lopez, Ph.D. 2011, who was both a Hubble and an Einstein fellow and is now an associate professor at the Ohio State University studying the lives and deaths of stars. "In the Zoom era, I can immediately message the department chair and say, 'Speak up right now,' and he does."

When people in the audience at a presentation ask questions belligerently, Berg responds, "Do you feel better? Can I continue?" Catherine Zucker—Ph.D. 2020, a Hubble fellow at STScI who works on the interstellar medium—redirects: "I just say, 'Let's touch base afterward,' and no one ever does."

MOST NOTABLY, the new generation of astronomers is not being quiet about sexual harassment, which, in spite of great publicity and its breach of every code of conduct at every institution, is still common: a 2018 NAS report found that 58 percent of women in STEM academia had been sexually harassed, and only 6 percent of them reported it. But a discontinuity may have occurred in 2015 when an ongoing sexual harassment case involving prominent astronomer Geoffrey Marcy was reported by BuzzFeed and then many other major publications. Women now file harassment cases more often and name names, not only in the old whisper networks but also in the news and social media.

Emily Martin, Ph.D. 2018, a 51 Pegasi b fellow at the University of California, Santa Cruz, who builds instruments to study exoplanets, was a graduate student when her lab's married deputy director repeatedly said he had feelings for her. When she did not reciprocate, he confronted her. Nearing the end of her doctorate and feeling safer from him, she filed for a formal investigation with the Title IX office in charge of enforcing the university's sexual harassment policies. The office concluded that his behavior did not break policy by hindering her, because she had finished her degree and obtained a postdoctoral position. So she wrote an account for the website Medium, naming him.

Hörst reported a man who sexually harassed her to her university, but officials claimed he had done nothing wrong. She had been told that the same man had harassed other women, and because the others, worried about his vindictiveness, did not want to make his name public, Hörst agreed not to name him. She has suggested to conference organizers that the orientation of poster rows in meeting rooms should be changed so that presenters standing by theirs are always publicly visible and cannot be cornered.

Kathryne Daniel, Ph.D. 2015, an associate professor at Bryn Mawr College who works on theoretical galactic dynamics, says when she is sexually harassed, "I let them pretend it didn't happen, [or] I say, 'You must be so embarrassed.' There are no robust ways of reporting that protect the reporter."

Chomiuk has not been harassed, but when a proposed faculty visitor turned out to be an astronomer who was then on leave without pay from Caltech for sexual harassment, she argued against the appointment. This "led to drama," she says. Others apologized for him; people told Chomiuk "he says he didn't do it" and "we'd bring him in for the science." But in the end the department agreed with her. "I could have just let it go," she says, "but aaargh, I couldn't."

Uncertainty about whether your career will go up in flames, cynicism about institutional responses, advocacy on behalf of others and worry about the harassers' next targets are all standard responses to sexual harassment. In spite of the difficulties, young women increasingly do not let it go. Casey wrote a chain of tweets listing her own experiences and added, "To all the young folks out there: document abuse. If you don't want to share it now, one day you'll be in a position of greater power/freedom."

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THE OTHER ISSUE that young women astronomers speak up about is bias, the deep cultural belief that, for instance, women are good at certain things, and science is not one of them. Like sexual harassment, bias, both unconscious and explicit, is widely acknowledged and is covered in every code of conduct. Where it was once endemic and obvious, it now is slightly less endemic and operates just below the visible level. Urry has been on hiring and promotion committees for the past 30 years and says she still sometimes will see a man presented as a genius when he has not quite "done his genius thing yet," whereas people question whether a woman with comparable accomplishments did the work on her own. Melodie Kao—Ph.D. 2017, a former Hubble fellow and current Heising-Simons 51 Pegasi b fellow at the University of California, Santa Cruz, who studies the magnetic fields of planets and low-mass stars—says she herself has had to actively resist being harder on women's proposals.

A partial solution, beginning in 2018, has been to implement a system of "dual-anonymous" proposal review, that is, one in which neither the reviewers nor the proposers know the other group's identities. The major funding agencies and observatories now use dual anonymity, and although the results are based on a small sample, the success rates of women's proposals seem to have gone up, albeit not dramatically. "We're moving from conscious, overt, unapologetic discrimination to unconscious bias," says Laura Kreidberg, Ph.D. 2016, who won the Annie Jump Cannon Award and is founding director of the department of atmospheric physics of exoplanets at the Max Planck Institute for Astronomy in Heidelberg, Germany. "For now it's strong, but I have a huge amount of hope of getting rid of it."

Because bias and sexual harassment seem to have deep, perennial roots, a few young women say that they initially wanted to burn the whole system down. But then they thought that rather than destroy a culture, they could make their own. "We've come to know each other in enough numbers," Daniel says, "[that] we can start to make sure a woman is in every decision-making room."

Kreidberg is creating a wholly new department at her institution. She wants thinking to be more collaborative, "done at a blackboard," she says. "I want juniors to speak up and ask questions. And I want people to not have so many responsibilities they can't be creative—there's no way around long hours at the cost of other things, but I have a family, I'm a runner, I tango, and without these breaks, I run out of ideas." Berg leads a 50-person team: "Everyone knows what's going on; no cliques, and no cutting people out." Casey co-leads a group of more than 200 people whose rules are, "Don't worry about papers that disagree, address it in a future paper, and don't be a dick. Respect the human, let the science happen, and it'll work itself out."

This young cohort of women astronomers is exquisitely aware of earlier generations' generosity and of its own responsibility to future scientists. "We recognize the generations of women who reached down and pulled us up, and a lot of us think now we need to do the same," Werk says. Urry estimates that she has spent roughly a quarter to a third of her career changing the conditions for women. "You have to stay in the field to change things," Hörst says. "If it had been intolerable for Meg [Urry], I wouldn't be here."

Most of these young women mentor undergraduate and graduate students who are not necessarily their assigned advisees. Kao teaches workshops that she markets as being on early-career skills but that are also about vulnerability and emotions, "how we know when we need to tend to our boundaries or to take better care of other people." Others run programs and workshops on the entire constellation of bias issues. They offer classes for children interested in science. They serve on their institutions' Diversity, Equity and Inclusion (DEI) committees, and they note that the DEI work tends to be done mostly by women and minorities. "I'm trying to think of a woman who is not an activist," Medeiros says. Their activism in the past 10 or so years has particularly focused on the demographic populations whose numbers in the field are still too low: "Things are better for us," Knutson says, "but 'us' is still white": white people make up 60.1 percent of the U.S. population and 82 percent of astronomers. Astronomy's demographics are disturbing: 18.5 percent of Americans are Hispanic or Latino, but 5 percent of astronomers are; 13.4 percent of Americans are Black, but 2 percent of astronomers are. A recent NAS report called the numbers of people of color in astronomy "abysmally low."

"I'm a first-generation woman of color who has to learn a completely new world," says Melinda Soares-Furtado, Ph.D. 2020, a Hubble fellow at the University of Wisconsin–Madison, who studies stars with odd chemical abundances. "I can code-switch, but it's exhausting." Kao is first-generation Taiwanese American: "From day one I've struggled to belong in the space I'm in. Half the time I want to change my name." Lopez says, "I'm Mexican American and have cerebral palsy, so that's another set of hurdles." She once went to a meeting with maybe 40 people whose sexual orientation and race or ethnicity were something other than straight and white, and she was shocked at "how many of us had encountered the [assumption that] our advisers had done our work."

The restrictions that people at these intersections deal with resemble the barriers of Rubin's world: being the only one like you in the room means sometimes wondering whether you should even be in that room, and it means the other people in the room sometimes think you are incapable of doing what you have just done. "I'm never the only woman there, but for sure I'm the only Black woman," Manning says. "Isolation is weird—some days it's 'Why don't I go where I'm not being looked at like this,' and some days it's 'No, I need to be here so someone else can see me.'"

When I started talking to this bunch of young and sparkly women, I thought they might describe themselves as just astronomers, not women astronomers. What they have done is more interesting: they have reframed "astronomy" to necessarily include "women"—they have merged "women" into "astronomy."

For instance, those of them offered the Annie Jump Cannon Award that Burbidge rejected have accepted it with pleasure and not as a prize for people who would not otherwise win prizes. The point, they say, is that they are women; they cannot escape it, and they might as well go ahead and have green hair, wear dresses to conferences and win women's prizes. They have been intelligent, creative and hardworking all along, but now they are also conspicuous; they have made themselves, as Manning says, seen. They are like Vera Rubin, slapping the lady-shaped icon on the door and telling the rest of their world to get used to it. SA

Ann Finkbeiner is a science writer based in Baltimore. She specializes in writing about astronomy and cosmology, grief, and the intersection of science and national security. She is co-proprietor of the science blog The Last Word on Nothing.

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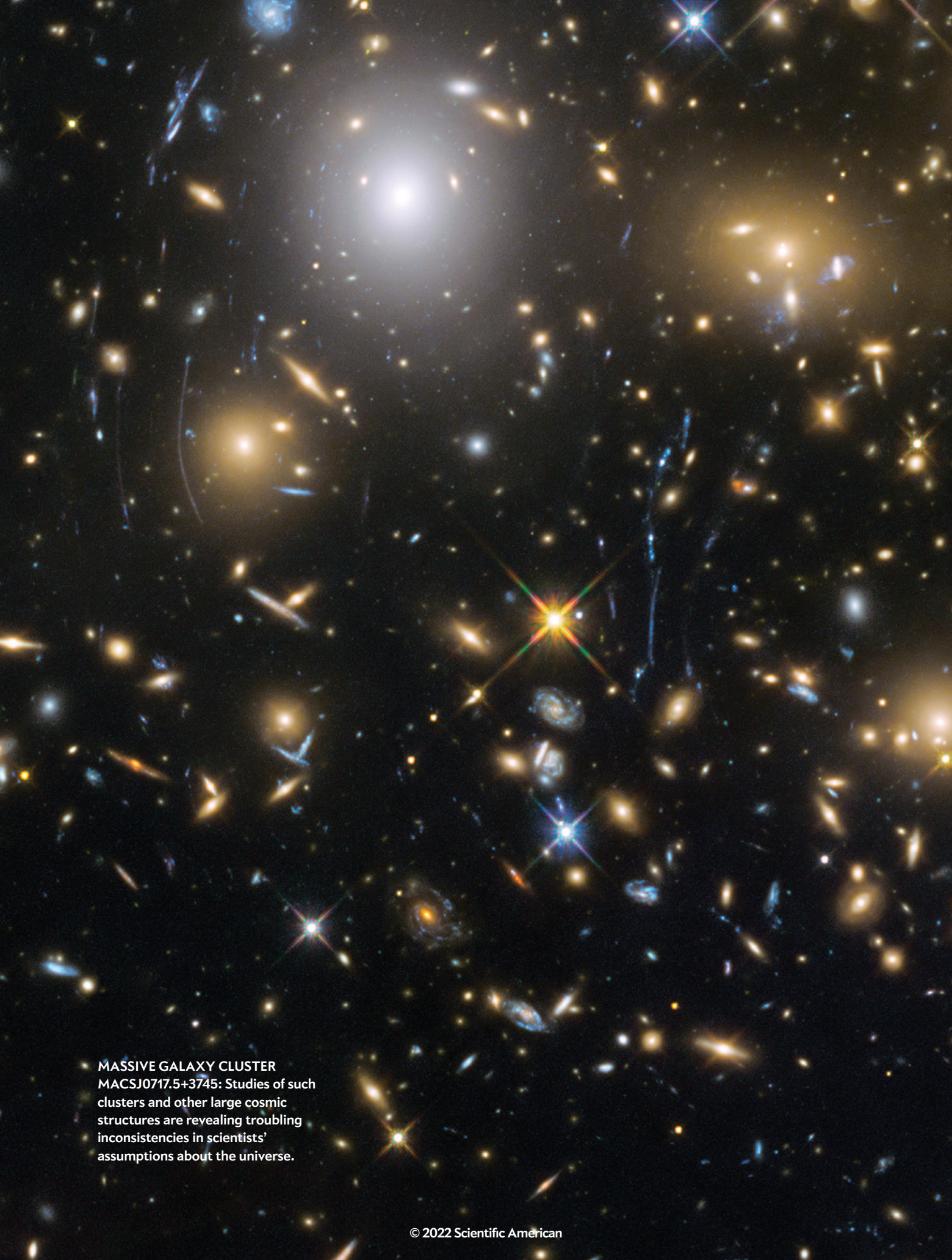

MASSIVE GALAXY CLUSTER MACSJ0717.5+3745: Studies of such clusters and other large cosmic structures are revealing troubling inconsistencies in scientists' assumptions about the universe.

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TWIN TENSIONS

A debate over conflicting measurements of key cosmological properties is poised to shape the next decade of astronomy and astrophysics

By Anil Ananthaswamy

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HOW FAST IS THE UNIVERSE EXPANDING? HOW MUCH DOES MATTER CLUMP up in our cosmic neighborhood? Scientists use two methods to answer these questions. One involves observing the early cosmos and extrapolating to present times, and the other makes direct observations of the nearby universe. But there is a problem. The two methods consistently yield different answers. The simplest explanation for these discrepancies is merely that our measurements are somehow erroneous, but researchers are increasingly entertaining another, more breathtaking possibility: These twin tensions—between expectation and observation, between the early and late universe—may reflect some deep flaw in the Standard Model of cosmology, which encapsulates our knowledge and assumptions about the universe. Finding and fixing that flaw could transform our understanding of the cosmos.

One way or another, an answer seems certain to emerge over the coming decade, as new space and terrestrial telescopes give astronomers clearer cosmic views. "Pursuing these tensions is a great way to learn about the universe," says astrophysicist and Nobel laureate Adam Riess of Johns Hopkins University. "They give us the ability to focus our experiments on very specific tests, rather than just making it a general fishing expedition."

These new telescopes, Riess anticipates, are about to usher in the third generation of precision cosmology. The first generation came in the 1990s and early 2000s with the Hubble Space Telescope and with NASA's WMAP satellite, which sharpened our measurements of the universe's oldest light, the cosmic microwave background (CMB). This first generation was also shaped by eight-meter-class telescopes in Chile and the twin 10-meter Keck behemoths in Hawaii.

Collectively, these observatories helped cosmologists formulate the Standard Model, which holds that the universe is a cocktail of 5 percent ordinary matter, 27 percent dark matter and 68 percent dark energy. The Standard Model can account with uncanny accuracy for most of what we observe about galaxies, galaxy clusters, and other large-scale structures and their evolution over cosmic time. Ironically, by its very success, the model highlights what we do not know: the exact nature of 95 percent of the universe.

Driven by even more precise measurements of the CMB from the European Space Agency's Planck satellite and various ground-based telescopes, the second generation of precision cosmology supported the Standard Model but also brought to light the tensions. The focus shifted to reducing so-called systematics: repeatable errors that creep in because of faults in the design of experiments or equipment.

The third generation is only now starting to take the stage with the successful launch and deep-space deployment of Hubble's successor, the James Webb Space Telescope (JWST). On Earth, radio telescope arrays such as the Simons Observatory in the Atacama Desert in Chile and the CMB-S4, a future assemblage of 21 dishes and half a million cryogenically cooled detectors that will be divided between sites in the Atacama and at the South Pole, should take CMB measurements with Planck-surpassing levels of precision.

The centerpieces of the third generation will be telescopes that stare at wide swaths of the sky. The first of these is likely to be the ESA's 1.2-meter Euclid space telescope, due for launch in 2023. Euclid will study the shapes and distributions of billions of galaxies with a gaze that spans about a third of the sky. Its observations will dovetail with those of NASA's Nancy Grace Roman Space Telescope, a 2.4-meter telescope with a field of view about 100 times bigger than Hubble's, which is slated for launch in 2025. Finally, when it begins operations in the mid-2020s, the ground-based Vera C. Rubin Observatory in Chile will map the entire overhead sky every few nights with its 8.4-meter mirror and a three-billion-pixel camera, the largest ever built for astronomy. "We're not going to be limited by noise and by systematics, because these are independent observatories," says astrophysicist Priyamvada Natarajan of Yale University. "Even if we have a systematic in our framework, we should [be able to] figure it out."

SCALING THE DISTANCE LADDER

RIESS WOULD LIKE to see a resolution of the Hubble tension, which arises from differing estimates of the value of the Hubble constant, H_0—the rate at which the universe is expanding. Riess leads a project called Supernovae, H_0, for the Equation of State of Dark Energy (SH0ES). The goal is to measure H_0, starting with the first rung of the so-called cosmic distance ladder, a hierarchy of methods to gauge ever greater celestial expanses.

The first rung—the one concerning the nearest cosmic objects—relies on determining the distance to special stars called Cepheid variables, which pulsate in proportion to their intrinsic luminosity. The longer the pulsation, the brighter the Cepheid. This relation between variability and luminosity makes Cepheids benchmark "standard candles" for determining distances

NASA/ESA/HST Frontier Fields Team (STScI) *(preceding pages)*

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A NOCTURNAL VIEW of the South Pole Telescope, one of several radio observatories mapping patterns in the cosmic microwave background.

Danvis Collection/Alamy Stock Photo

around the Milky Way and nearby galaxies. They also form the basis of the cosmic distance ladder's second rung, in which astronomers gauge distances to more remote galaxies by comparing Cepheid-derived estimates with those from another, more powerful set of standard candles called type Ia (pronounced "one A") supernovae, or SNe Ia.

Ascending further, astronomers locate SNe Ia in even more far-flung galaxies, using them to establish a relation between distance and a galaxy's redshift, a measure of how fast it is moving away from us. The result is an estimate of H_0.

In December 2021, Riess says, "after a couple of years of taking a deep dive on the subject," the SH0ES team and the Pantheon+ team, which has compiled a large data set of type Ia supernovae, announced the results of nearly 70 different analyses of their combined data. The data included observations of Cepheid variables in 37 host galaxies that contained 42 type Ia supernovae, more than double the number of supernovae studied by SH0ES in 2016. Riess and his co-authors suspect this latest study represents the Hubble's last stand, the outer limits of that hallowed telescope's ability to help them climb higher up the cosmic scale. The set of supernovae now includes "all suitable SNe Ia—of which we are aware—observed between 1980 and 2021" in the nearby universe. In their analysis, H_0 comes out to be 73.04 ± 1.04 kilometers per second per megaparsec.

That number is way off the value obtained by an entirely different method that looks at the other end of cosmic history—the so-called epoch of recombination, when the universe became transparent to light, about 380,000 years after the big bang. The light from this epoch, now stretched to microwave wavelengths because of the universe's subsequent expansion, is detectable as the all-pervading cosmic microwave background. Tiny fluctuations in temperature and polarization of the CMB capture an important signal: the distance a sound wave travels from almost the beginning of the universe to the epoch of recombination.

This length is a useful metric for precision cosmology and can be used to estimate the value of H_0 by extrapolating to the present-day universe using the standard LCDM model. (L stands for lambda or dark energy, and CDM for cold dark matter; cold refers to the assumption that dark matter particles are relatively slow-moving.) Published in 2021, the latest analysis combined data from the Planck satellite and two ground-based instruments, the Atacama Cosmology Telescope and the South Pole Telescope, to arrive at an H_0 of 67.49 ± 0.53.

The discrepancy between the two estimates has a statistical significance of five sigma, meaning there is only about a one-in-a-million chance of its being a statistical fluke. "It's certainly at the level that people should take seriously," Riess says. "And they have."

HOW CLUMPY IS THE COSMOS?

THE OTHER TENSION that researchers are starting to take seriously concerns a cosmic parameter called S_8, which depends on the density of matter in the universe and the extent to which it is

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clumped up rather than evenly distributed. Estimates of S_8 also involve, on one end, measurements of the CMB and, on the other, measurements of the local universe. The CMB-derived value of S_8 in the early universe, extrapolated using LCDM, generates a present-day value of about 0.834.

The local universe measurements of S_8 involve a host of different methods. Among the most stringent are so-called weak gravitational lensing observations, which measure how the average shape of millions of galaxies across large patches of the sky is distorted by the gravitational influence of intervening concentrations of dark and normal matter. Astronomers used the latest data from the Kilo-Degree Survey, which more than doubled its sky coverage from 350 to 777 square degrees of the sky (the full moon, by comparison, spans a mere half a degree) and estimated S_8 to be about 0.759. The tension between the early- and late-universe estimates of S_8 has grown from 2.5 sigma in 2019 to three sigma now (or a one-in-740 chance of being a fluke). "This tension isn't going away," says astronomer Hendrik Hildebrandt of Ruhr University Bochum in Germany. "It has hardened."

There is yet another way to arrive at the value of S_8: by counting the number of the most massive galaxy clusters in some volume of space. Astronomers can do that directly—for example, by using gravitational lensing. They can also count clusters by studying their imprint on the cosmic microwave background, thanks to something called the Sunyaev-Zeldovich effect. (This effect causes CMB photons to scatter off the hot electrons in clusters of galaxies, creating shadows in the CMB that are proportional to the mass of the cluster.)

A detailed 2019 study that used data from the South Pole Telescope estimated S_8 to be 0.749—again, way off from the CMB+LCDM-based estimates. These numbers could be reconciled if the estimates of the masses of these clusters were wrong by about 40 to 50 percent, Natarajan says, although she thinks such substantial revisions are unlikely. "We are not that badly off in the measurement game," she says. "So that's another kind of internal inconsistency, another anomaly pointing to something else."

BREAKING THE TENSIONS

GIVEN THESE TENSIONS, it is no surprise that cosmologists are anxiously awaiting fresh data from the new generation of observatories. For instance, David Spergel of Princeton University is eager for astronomers to use JWST to study the brightest of the so-called red-giant-branch stars. These stars have a well-known luminosity and can be used as standard candles to measure galactic distances—an independent rung on the cosmic ladder, if you will. In 2019 Wendy Freedman of the University of Chicago and her colleagues used this technique to estimate H_0, finding that their value sits smack in the middle of the early- and late-universe estimates. "The error bars on the current tip of the red-giant-branch data are such that they're consistent with both possibilities," Spergel says. Astronomers are also planning to use JWST to recalibrate the Cepheids surveyed by Hubble, and separately the telescope will help create another new rung for the distance ladder by targeting Mira stars (which, like Cepheids, have a luminosity-periodicity relation useful for cosmic cartography).

JWST might resolve or strengthen the H_0 tension, and the wide-field survey data from the Euclid, Roman and Rubin observatories could do the same for the S_8 tension by studying the clustering and clumping of matter. The sheer amount of data expected from this trio of telescopes will reduce S_8 error bars enormously. "The statistics are going to go through the roof," Natarajan says.

Meanwhile theoreticians are already having a field day with the twin tensions. "This is a playground for theorists," Riess says. "You throw in some actual observed tensions, and they are having more fun than we are."

The most recent theoretical idea to receive a great deal of interest is something called early dark energy (EDE). In the canonical LCDM model, dark energy started dominating the universe relatively late in cosmic history, only about five billion years ago. But, Spergel says, "we don't know why dark energy is the dominant component of the universe today. Because we don't know why it's important today, it could have also been important early on." That is partly the rationale for invoking dark energy's effects much earlier, before the epoch of recombination. Even if dark energy was just 10 percent of the universe's energy budget during those times, that would be enough to accelerate the early phases of cosmic expansion, causing recombination to occur sooner and shrinking the distance traversed by primordial sound waves. The net effect would be to ease the H_0 tension.

> "We don't know why dark energy is the dominant component of the universe today."
> —David Spergel *Princeton University*

"What I find most interesting about these models is that they can be wrong," Spergel says. Cosmologists' EDE models make predictions about the resulting EDE-modulated patterns in the photons of the CMB. In February 2022 Silvia Galli, a member of the Planck collaboration at the Sorbonne University in Paris, and her colleagues published an analysis of observations from Planck and ground-based CMB telescopes, suggesting that they collectively favor EDE over LCDM by a statistical smidgen. Confirming or refuting this tentative result will require more and better data—which could come soon from upcoming observations by the same ground-based CMB telescopes. But even if EDE models prove to be better fits and fix the H_0 tension, they do little to alleviate the tension from S_8.

Potential fixes for S_8 exhibit a similarly vexing lack of overlap with H_0. In March 2022 Guillermo Franco Abellán of the University of Amsterdam and his colleagues published a study in *Physical Review D* showing that the S_8 tension could be eased by the hypothetical decay of cold dark matter particles into one massive particle and one "warm" massless particle. This mechanism would lower the value of S_8 arising from CMB-based extrapolations, bringing it more in line with the late-universe measurements. Unfortunately, it doesn't solve the H_0 tension. "It seems like a robust pattern: whatever model you come up with that solves the H_0 tension makes the S_8 tension worse, and the other way around," Hildebrandt says. "There are a few models that at least don't make the other tension worse, but [they] also don't improve it a lot."

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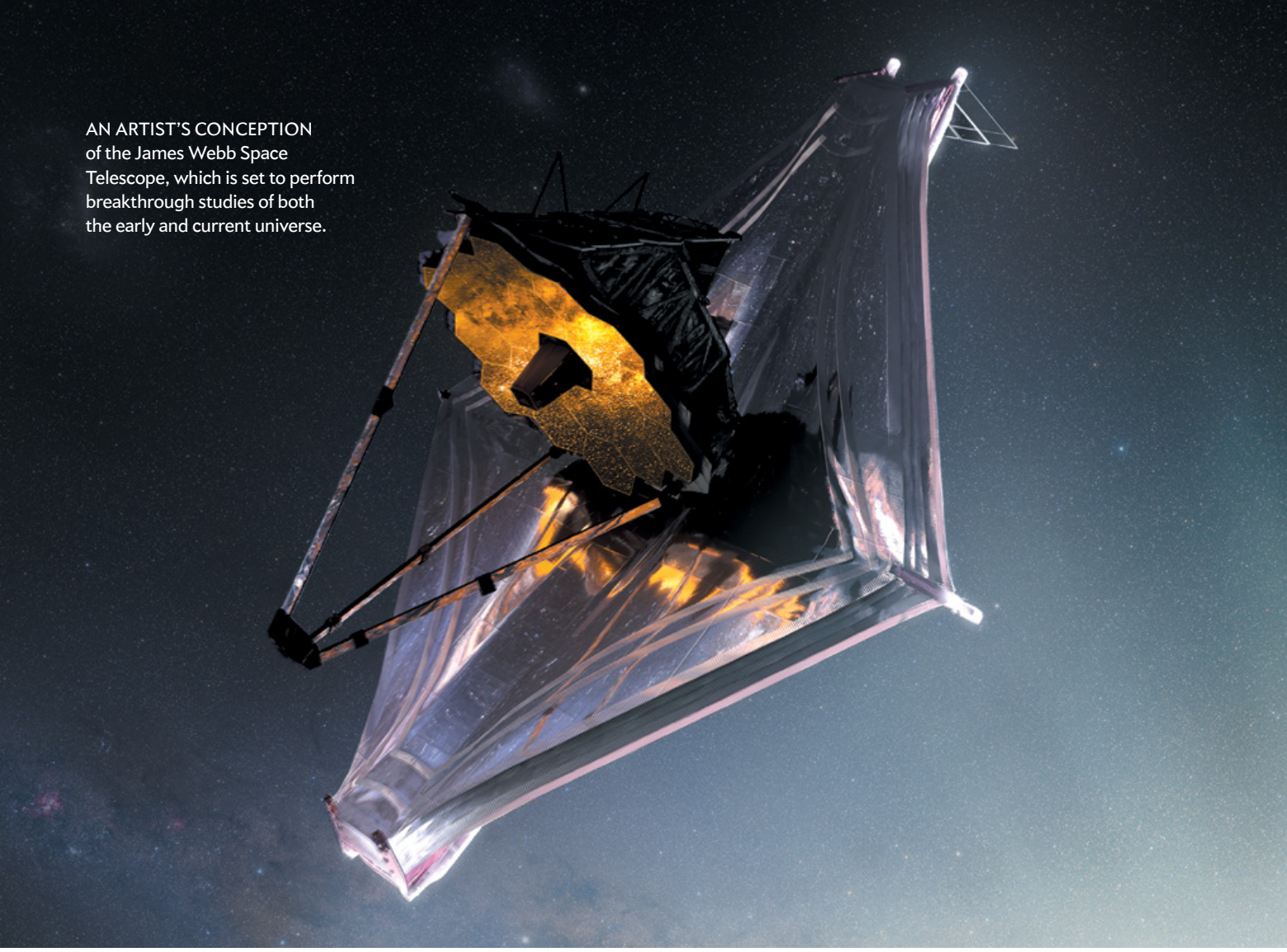

AN ARTIST'S CONCEPTION of the James Webb Space Telescope, which is set to perform breakthrough studies of both the early and current universe.

NASA/GSFC/CIL/Adriana Manrique Gutierrez

"WE ARE MISSING SOMETHING"

ONCE FRESH DATA arrive, Spergel foresees a few possible scenarios. First, the new CMB data could turn out to be consistent with early dark energy, resolving the H_0 tension, and the upcoming survey telescope observations could separately ease the S_8 tension. That would be a win for early dark energy models—and would constitute a major shift in our understanding of the opening chapters of cosmic history. It's also possible that both H_0 and S_8 tensions resolve in favor of LCDM. This would be a win for the Standard Model and a possibly bittersweet victory for cosmologists hoping for paradigm-shifting breakthroughs. Of course, it might turn out that neither tension is resolved. "Outcome three would be both tensions become increasingly significant as the data improve—and early dark energy isn't the answer," Spergel says. Then, LCDM would presumably have to be reworked differently, although how is unclear.

Natarajan thinks that the tensions and discrepancies are probably telling us that LCDM is merely an "effective theory," a technical term meaning that it accurately explains a certain subset of the current compendium of cosmic observations. "Perhaps what's really happening is that there is an underlying, more complex theory," she says. "And that LCDM is this [effective] theory, which seems to have most of the key ingredients. For the level of observational probes we had previously, that effective theory was sufficient." But times change, and the data deluge from precision cosmology's third generation of powerful observatories may demand more creative and elaborate theories.

Theorists, of course, are happy to oblige. For instance, Spergel speculates that if early dark energy could interact with dark matter (in LCDM, dark energy and dark matter do not interact), this arrangement could suppress the fluctuations of matter in the early universe in ways that would resolve the S_8 tension while simultaneously taking care of the H_0 tension. "It makes the models more baroque," Spergel says, "but maybe that's what nature will demand."

As an observational astronomer, Hildebrandt is circumspect. "If there was a convincing model that beautifully solves these two tensions, we'd already have the next Standard Model," he says. "That we're instead still talking about these tensions and scratching our heads is just reflecting the fact that we don't have such a model yet." Riess agrees. "After all, this is a problem of using a model based on an understanding of physics and the universe that is about 95 percent incomplete, in terms of the nature of dark matter and dark energy," he says. "It wouldn't be crazy to think that we are missing something." SA

Anil Ananthaswamy is author of *The Edge of Physics* (Houghton Mifflin Harcourt, 2010), *The Man Who Wasn't There* (Dutton, 2015), and, most recently, *Through Two Doors at Once: The Elegant Experiment That Captures the Enigma of Our Quantum Reality* (Dutton, 2018).

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This Hot Summer Is One of the Coolest of the Rest of Our Lives

Heat waves broke temperature records around the world during the summer of 2022, but it will still be one of the coolest summers of the next few decades

By Andrea Thompson

Extreme heat was a constant in the news last summer: In July a punishing heat wave in Europe pushed temperatures across parts of the U.K. above 104 degrees Fahrenheit (40 degrees Celsius) for the first time in history. That same month was viciously hot across China, including in Shanghai—home to 26 million people—which tied its highest-ever July reading of 105.6 degrees F (40.9 degrees C). And even before the summer officially began, searing heat settled over the U.S. South in May. Amarillo, Tex., recorded its earliest day with temperatures topping 100 degrees F (37.8 degrees C), and Abilene, Tex., endured 14 straight days of 100 degrees F or higher, doubling its previous streak.

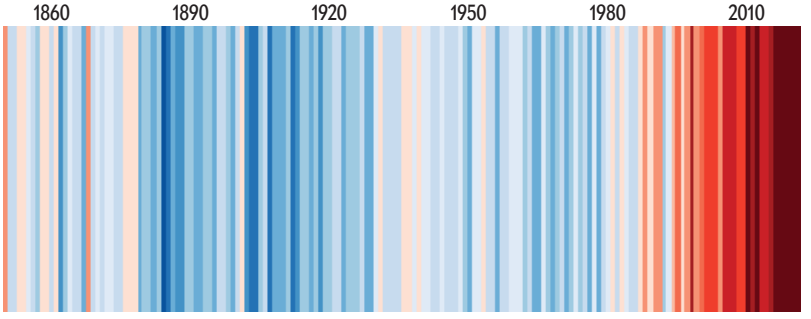
Those were just a few of the events that contributed to the Northern Hemisphere's land areas experiencing their second-warmest June and third-warmest July on record, according to the National Oceanic and Atmospheric Administration. But temperatures that make big news today may seem ho-hum—even relatively cool—within a couple of decades, as the continued burning of fossil fuels pushes baseline temperatures ever higher. Heat waves are also becoming longer and more frequent. Not every summer will be hotter than the one just before it, of course, but global warming means that the heat records set today will eventually fall down the charts. As U.S. Secretary of Commerce Gina Raimondo said during the July launch of Heat.gov, a government website for heat information, "The reality is, given the scientific predictions, this summer—with its oppressive and widespread heat waves—is likely to be one of the coolest summers of the rest of our lives."

In a world without human-caused climate change, we would expect to see records set fairly randomly, following the whims of our planet's natural variations in climate. But global warming has effectively loaded the dice, with record heat outpacing record cold. This imbalance is starkly evident in the famous "warming stripes" graphics created by climate scientist Ed Hawkins of the University of Reading in England. These graphics render each year's average temperature as a shade of red or blue, depending on how much above or below the long-term average it is. The version on this page shows summer temperatures going back to the mid-19th century for the land areas of the Northern Hemisphere, relative to the average for 1971–2000. Although there is the odd pink or orange year scattered throughout the record, the pileup of deep red bars in recent decades immediately jumps out. Even 1998—which at the time was far and away the hottest summer (and year) on record because of an exceptionally strong El Niño event—has been far surpassed. Similarly, the 1990s were supplanted as the hottest decade by the 2000s, which were then replaced by the 2010s. The 2020s will eventually follow suit.

Natural variation of course still plays a role from year to year and month to month. For example, July 2021 was the warmest July on record for land in the Northern Hemisphere, whereas this past July came in third place. Such variations become more pronounced the more locally one looks. A relatively small area such as the U.K. can still have summers with normal temperatures in any given year. "For an individual, wherever you

Summer Shows Its Stripes

Each stripe shows the temperature difference over land in the Northern Hemisphere for one year, relative to the average of 1971–2000. Years when temperatures were lower have **blue** stripes, and warmer years have **red** stripes. Darker shades indicate more extreme differences, compared with the reference years.



Source: Met Office U.K.

Graphic by Ed Hawkins

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Chris Gorman/Getty Images

Beachgoers crowd the seashore in Brighton, England, in July 2022. The U.K. experienced record-breaking temperatures last summer.

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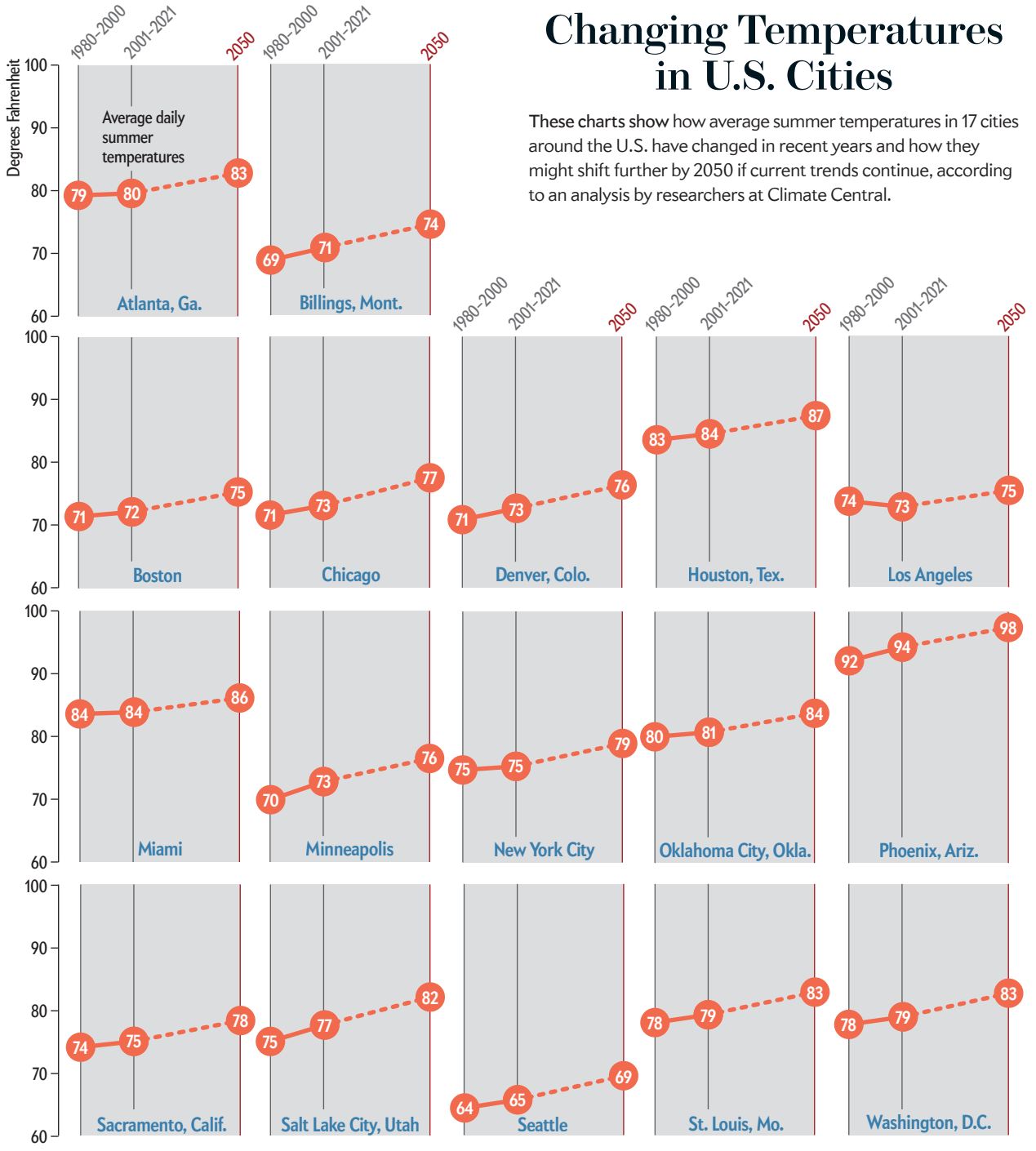
Changing Temperatures in U.S. Cities

These charts show how average summer temperatures in 17 cities around the U.S. have changed in recent years and how they might shift further by 2050 if current trends continue, according to an analysis by researchers at Climate Central.



live, there will be colder summers than this going forward," Hawkins says. For example, in England, which bore the brunt of last July's heat wave in Europe, plenty of recent summers have seen temperatures at or below the long-term average. And several hot summers from the 1970s, 1980s and 1990s still rank among England's hottest—including the standout summer of 1976, which is still a touchstone in the country's collective memory. (That summer saw prolonged heat and drought, the latter of which also helps to increase temperatures.)

But "even if there's a few colder years after this, it doesn't mean climate change has gone away," says Vikki Thompson, a climate scientist at the University of Bristol in England. The influence of climate change is still clear: average summer temperatures in England have steadily increased over recent decades, as they have everywhere. This can be seen in an analysis of past, present and projected future average summer temperatures for cities across the U.S. in the graphic above. Chicago's average summer temperature, for in-

Source: Climate Central

Graphics by Amanda Montañez

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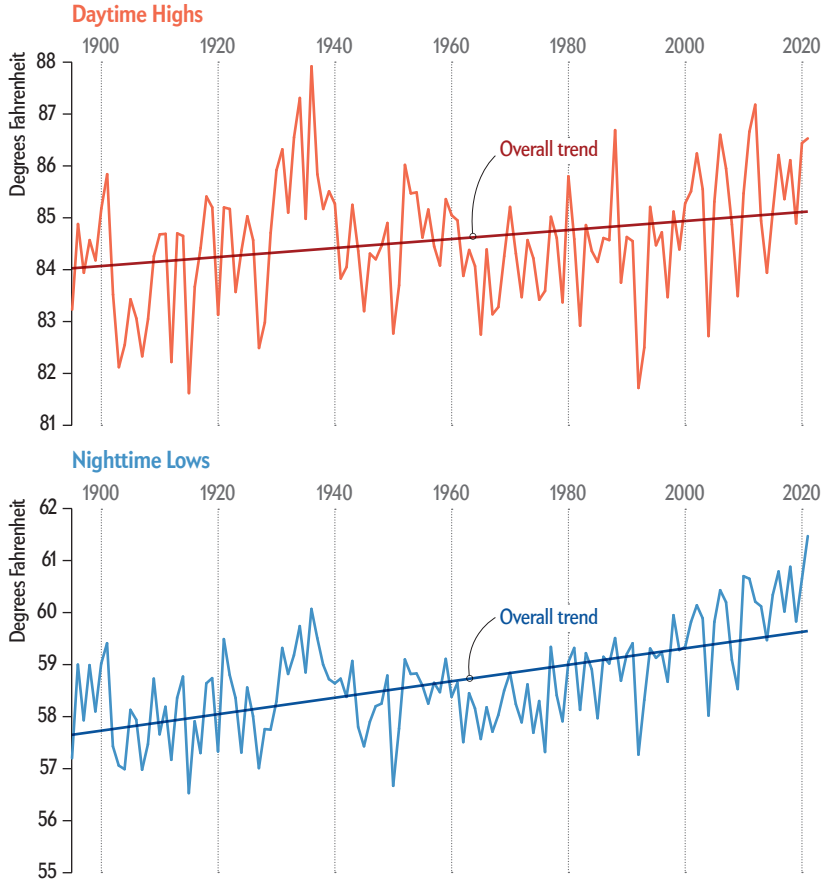
Highs and Lows

These charts show average high and low temperatures during U.S. summers from 1895 to 2021. Certain regions may experience cooler summers going forward, but average temperatures will continue to rise, with more frequent record-breaking years. As overall nighttime temperatures increase, human bodies are less able to cool off, amplifying the effects of heat waves.



Source: NOAA National Centers for Environmental Information, Climate at a Glance: National Time Series

stance, was 71 degrees F in the late 20th century; today it averages about 73 degrees F. In one of the higher-emissions scenarios of the future, it could average 77 degrees F. (These averages include both daytime and nighttime temperatures.)

THIS STEADILY RISING BASELINE MEANS that when heat waves do hit, they are worse than they would have been in the absence of climate change. An analysis of this past July's U.K. heat wave, conducted by scientists at the World Weather Attribution consortium, found that in the absence of climate change, temperatures during such an event would have topped out around 96.8 degrees F (36 degrees C). In another decade or two, a similar event would probably lead to even higher temperatures than recorded this year.

Even heat waves that don't set daily temperature records can be made worse by climate change. Although the southern U.S. is used to hot summers, several prolonged heat events in 2022 had highs above 100 degrees F across large areas for days at a time. Because of this, Texas recorded its hottest April–July on record and saw the average maximum temperature for July top 100 degrees F for the first time. "There were no, say, 10-day periods that are off-the-charts huge, but it's just been relentless," says NOAA climate scientist Derek Arndt. A recent *Washington Post* analysis of data from the nonprofit First Street Foundation found that long stretches of hot weather will become more frequent and last longer across the U.S., particularly in the South. Nearly half of all Americans now experience at least three consecutive days that are 100 degrees F or hotter each year, and that will increase to two thirds in the coming decades. Some parts of the South could see 70 such consecutive days.

And daytime temperatures are not the only consideration. Overnight lows have been rising far faster than daytime highs in the contiguous U.S., as can be seen in the graphic on this page. Health-wise, night is when the body would usually get a break from the summer heat—so as overnight lows rise, that recovery period becomes less available. "You can't cool down, so you're starting the next day at that high level," Thompson says. This can take a big toll on both physical and mental health.

THE CAPACITY OF POPULATIONS TO COPE with ever increasing and more frequent heat extremes is a key concern of the current climate emergency. Several places that are famous for cooler summers, such as the U.K. and the U.S. Pacific Northwest, have not built the infrastructure to cope with extreme heat. Many homes in these and other areas lack air-conditioning—which many may not be able to readily afford. Such constraints make it more likely that people will experience the ill health effects of heat. Even in areas accustomed to hot weather, such as Texas, prolonged extreme heat can ramp up air-conditioner use and strain the power grid.

Exactly how hot our future summers are, and how miserable we get on hot nights, is, to some degree, in our own hands. The more we curtail fossil-fuel burning now, the more we can constrain the global temperature rise that is fueling ever hotter summers. But even if we bring greenhouse gas emissions under control, we will still have to live in a hotter climate than we did in the past. That reality means helping people adapt, whether through building or retrofitting infrastructure to withstand heat, subsidizing air-conditioning or simply making sure that people have ample warning of extreme heat—and that they know how to avoid its ill health effects. "It's our choices that make a difference," Hawkins says. SA

Andrea Thompson, an associate editor at *Scientific American,* covers sustainability.

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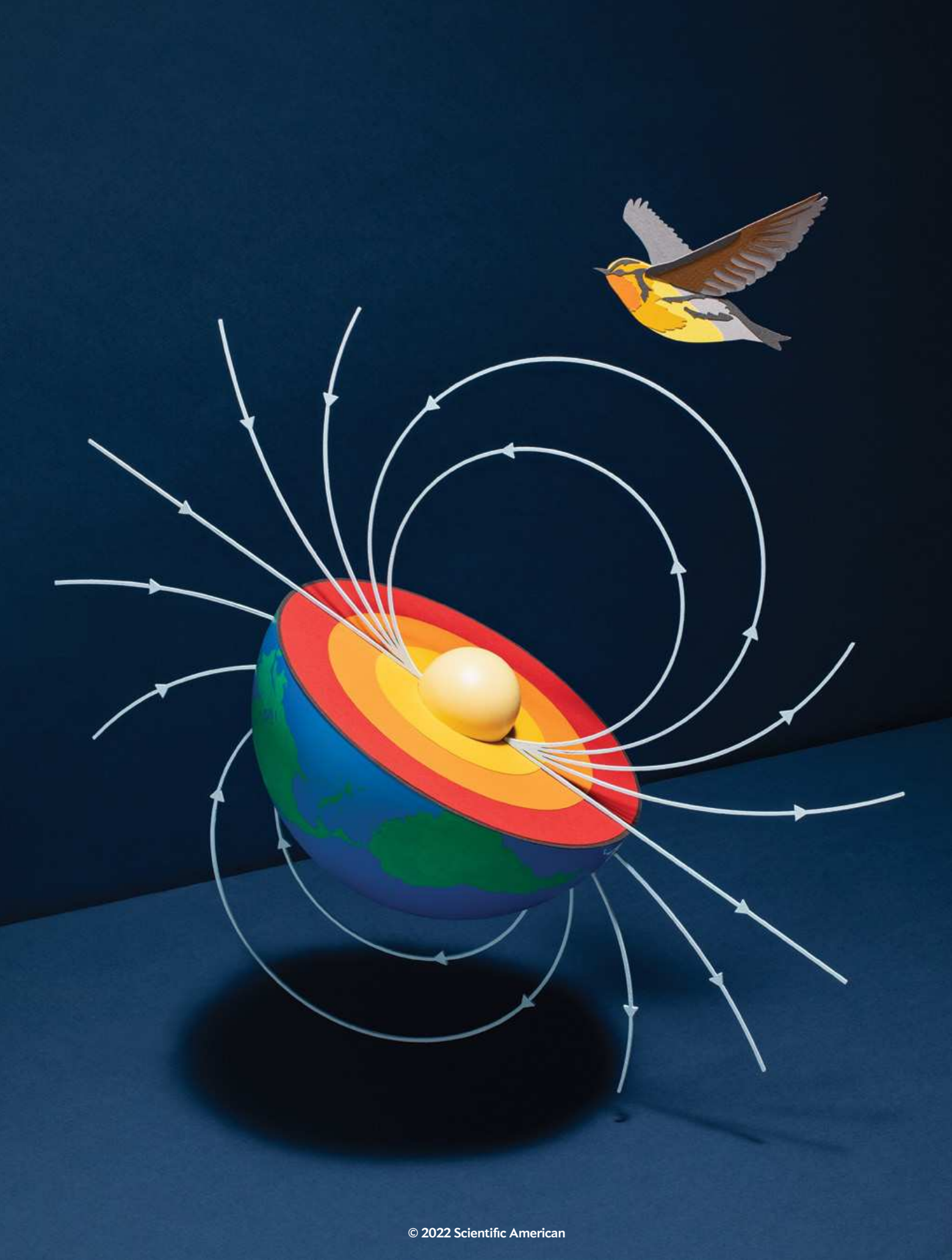

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The Quantum Nature of Bird Migration

Migratory birds travel vast distances between their breeding and wintering grounds. New research hints at the biophysical underpinnings of their internal navigation system

By Peter J. Hore and Henrik Mouritsen

Illustration by Kyle Bean

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IMAGINE YOU ARE A YOUNG BAR-TAILED GODWIT, A LARGE, LEGGY SHOREBIRD WITH a long, probing bill hatched on the tundra of Alaska. As the days become shorter and the icy winter looms, you feel the urge to embark on one of the most impressive migrations on Earth: a nonstop transequatorial flight lasting at least seven days and nights across the Pacific Ocean to New Zealand 12,000 kilometers away. It's do or die. Every year tens of thousands of Bar-tailed Godwits complete this journey successfully. Billions of other young birds, including warblers and flycatchers, terns and sandpipers, set out on similarly spectacular and dangerous migrations every spring, skillfully navigating the night skies without any help from more experienced birds.

People have long puzzled over the seasonal appearances and disappearances of birds. Aristotle thought that some birds such as swallows hibernated in the colder months and that others transformed into different species—redstarts turned into robins for the winter, he proposed. Only in the past century or so, with the advent of bird banding, satellite tracking and more widespread field studies, have researchers been able to connect bird populations that winter in one area and nest in another and show that some travel vast distances between the two locales every year. Remarkably, even juvenile long-haul travelers know where to go, and birds often take the same routes year after year. How do they find their way?

Migrating birds use celestial cues to navigate, much as sailors of yore used the sun and stars to guide them. But unlike humans, birds also detect the magnetic field generated by Earth's molten core and use it to determine their position and direction. Despite more than 50 years of research into magnetoreception in birds, scientists have been unable to work out exactly how they use this information to stay on course. Recently we and others have made inroads into this enduring mystery. Our experimental evidence suggests something extraordinary: a bird's compass relies on subtle, fundamentally quantum effects in short-lived molecular fragments, known as radical pairs, formed photochemically in its eyes. That is, the creatures appear to be able to "see" Earth's magnetic field lines and use that information to chart a course between their breeding and wintering grounds.

A MYSTERIOUS SENSE

MIGRATORY BIRDS have an internal clock with an annual rhythm that tells them, among other things, when to migrate. They also inherit from their parents the directions in which they need to fly in the autumn and spring, and if the parents each have different genetically encoded directions, their offspring will end up with an intermediate direction. For example, if a southwest-migrating bird is crossed with a southeast-migrating bird, their offspring will head south when the time comes. But how do the young birds know which direction is southwest or south or southeast? They have at least three different compasses at their disposal: one allows them to extract information from the position of the sun in the sky, another uses the patterns of the stars at night, and the third is based on Earth's ever present magnetic field.

In their first autumn, young birds follow inherited instructions such as "fly southwest for three weeks and then south-southeast for two weeks." If they make a mistake or are blown off course, they are generally unable to recover because they do not yet have a functioning map that would tell them where they are. This is one of the reasons that only 30 percent of small songbirds survive their first migrations to their wintering grounds and back again. During its first migration a bird builds up a map in its brain that, on subsequent journeys, will enable it to navigate with an ultimate precision of centimeters over thousands of kilometers. Some birds breed in the same nest box and sleep on the same perch in their wintering range year after year. Equipped with this map, about 50 percent of adult songbirds make it back to their nesting site to breed every year.

Migratory birds' navigational input comes from several senses—mainly sight, smell and magnetoreception. By observing the apparent nighttime rotation of the stars around the North Star, the birds learn to locate north before they embark on their first migration, and an internal 24-hour clock allows them to calibrate their sun compass. Characteristic smells can help birds recognize places they have visited before. Scientists know a great deal about the detailed biophysical mechanisms of the birds' senses of sight and smell. But the inner workings of their magnetic compass have proved harder to understand.

The magnetic direction sense in small songbirds that migrate at night is remarkable in several important respects. First, observations of caged birds exposed to carefully controlled magnetic fields show that their compass does not behave like the magnetized needle in a ship's compass. A bird detects the axis of the magnetic field and the angle it makes with Earth's surface, the so-called inclination compass. In laboratory experiments, inverting the magnetic field's direction so that it points in exactly the opposite direction has no effect on the bird's ability to orient correctly. Second, a bird's perception of Earth's magnetic field can be disrupted by extraordinarily weak magnetic fields that reverse their direction several million times per second. Last, even though songbirds fly at night under the dim light of the stars, their magnetic compass is light-dependent, hinting at a link between vision and magnetic sensing.

In 1978, in an attempt to make sense of these features of avian magnetoreception, Klaus Schulten, then at the Max Planck Institute for Biophysical Chemistry in Göttingen, Germany, put forth a remarkable idea: that the compass relies on magnetically sensitive chemical transformations. At first glance, this proposal seems preposterous because the energy available from Earth's magnetic field is millions of times too small to break, or even significantly weaken, the bonds between atoms in molecules. But Schulten was inspired by the discovery 10 years previously that short-lived chemical intermediates known as radical pairs have unique properties that make

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their chemistry sensitive to feeble magnetic interactions. Over the past 40 years researchers have conducted hundreds of lab studies of radical-pair reactions that are affected by the application of magnetic fields.

To appreciate why radical pairs are so special, we need to talk about a quantum-mechanical property of the electron known as spin angular momentum, or "spin" for short. Spin is a vector with a direction as well as a magnitude, and it is often represented by an arrow, ↑ or ↓, for example. Particles with spin have magnetic moments, which is to say they behave like microscopic magnets. Most molecules have an even number of electrons arranged in pairs with opposed spins (↑↓), which therefore cancel each other out. Radicals are molecules that have lost or gained an electron, meaning that they contain an odd, unpaired, electron and hence have a spin and a magnetic moment. When two radicals are created simultaneously by a chemical reaction (this is what we mean by radical pair), the two unpaired electrons, one in each radical, can have either antiparallel spins (↑↓) or parallel spins (↑↑), arrangements known as singlet and triplet states, respectively.

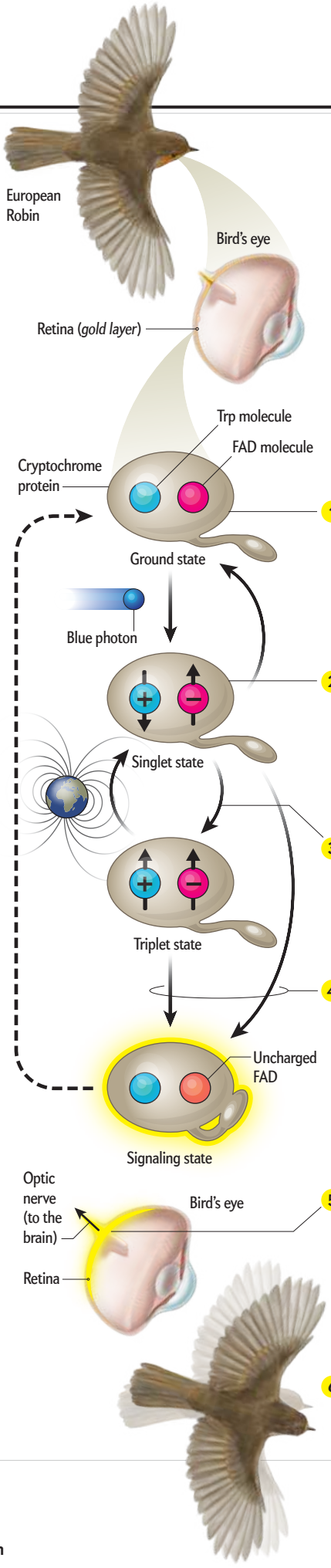
Immediately after a radical pair is created in a singlet state, internal magnetic fields cause the two electronic spins to undergo a complex quantum "waltz" in which singlet turns into triplet and triplet turns back into singlet millions of times per second for periods of up to a few microseconds. Crucially, under the right conditions, this dance can be influenced by external magnetic fields. Schulten suggested that this subtle quantum effect could form the basis of a magnetic compass sense that might respond to environmental stimuli a million times weaker than would normally be thought possible. Research that we and others have carried out in recent years has generated fresh support for this hypothesis.

A POSSIBLE MECHANISM

TO BE USEFUL, hypotheses need to explain known facts and make testable predictions. Two aspects of Schulten's proposed compass mechanism are consistent with what is known about the birds' compass: radical pairs are indifferent to exact external magnetic field reversals, and radical pairs are often formed when molecules absorb light. Given that the birds' magnetic compass is light-dependent, a prediction of Schulten's hypothesis is that their eyes play a part in the magnetic sensory system. About 10

The Compass Mechanism

Studies suggest that the magnetic compass of migratory birds relies on quantum effects in short-lived molecular fragments known as radical pairs that are formed photochemically in the eyes. In this way, the birds can perceive Earth's magnetic field lines and use that information to navigate their long-haul trips.



1. Cryptochrome proteins—located in the retinal cells of the bird's eye—include a flavin adenine dinucleotide molecule (FAD) and a tryptophan amino acid (Trp). In the stable state, these molecules are electrically neutral, and a small section of the protein probably extends like a tail.
2. When a photon of blue light hits the cryptochrome, an electron jumps from the Trp onto the FAD. The resulting molecules—each with an odd number of electrons—are known as a radical pair. In this singlet state, the molecules' unpaired electrons spin in opposition.
3. The activated protein oscillates rapidly back and forth between the singlet state and the triplet state, in which the unpaired electrons spin in parallel. Earth's magnetic field influences the spin, impacting the likelihood of each state dominating.
4. Both states can undergo chemical reactions that transform them into the "signaling state"—in which a hydrogen ion has been added to the FAD radical—and the tail seems to move closer to the body of the protein. The singlet state can also simply return to the ground state. The proportion of outcomes depends on the bird's orientation in Earth's magnetic field.
5. The signaling state of the cryptochrome turns on a biochemical cascade that triggers the release of neurotransmitter molecules in the retina. Signals continue to the bird's brain, where the magnetic information they contain is integrated with information from other directional cues, informing the direction of the bird's flight.
6. Cryptochrome returns to its ground state, and the process starts again (*dashed arrow*).

Graphic by Jillian Ditner (birds and eyes) and Jen Christiansen

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years ago the research group of one of us (Mouritsen) at the University of Oldenburg in Germany found that a brain region called Cluster N, which receives and processes visual information, is by far the most active part of the brain when certain night-migrating birds are using their magnetic compass. If Cluster N is dysfunctional, research in migratory European Robins showed, the birds can still use their sun and star compasses, but they are incapable of orienting using Earth's magnetic field. From experiments such as these, it is clear that the magnetic compass sensors are located in the birds' retinas.

One early objection to the radical-pair hypothesis was that no one had ever shown that magnetic fields as tiny as Earth's, which are 10 to 100 times weaker than a fridge magnet, could affect a chemical reaction. To address this point, Christiane Timmel of the University of Oxford and her colleagues chose a molecule chemically unlike anything one would find inside a bird: one that contained an electron donor molecule linked to an electron acceptor molecule via a molecular bridge. Exposing the molecules to green light caused an electron to jump from the donor to the acceptor over a distance of about four nanometers. The radical pair that formed from this reaction was extremely sensitive to weak magnetic interactions, proving that it is indeed possible for a radical-pair reaction to be influenced by the presence of—and, more important, the direction of—an Earth-strength magnetic field.

EUROPEAN ROBIN (*top*) and Bar-tailed Godwit (*bottom*) are among the many birds that migrate long distances.

Schulten's hypothesis also predicts that there must be sensory molecules (magnetoreceptors) in the retina in which magnetically sensitive radical pairs can be created using the wavelengths birds need for their compass to operate, which another line of research had identified as light centered in the blue region of the spectrum. In 2000 he suggested that the necessary photochemistry could take place in a then recently discovered protein called cryptochrome.

Cryptochromes are found in plants, insects, fish, birds and humans. They have a variety of functions, including light-dependent control of plant growth and regulation of circadian clocks. What makes them attractive as potential compass sensors is that they are the only known naturally occurring photoreceptors in any vertebrate that form radical pairs when they absorb blue light. Six types of cryptochromes have been found in the eyes of migratory birds, and no other type of candidate magnetoreceptor molecule has emerged in the past 20 years.

Like all other proteins, cryptochromes are composed of chains of amino acids folded up into complex three-dimensional structures. Buried deep in the center of many cryptochromes is a yellow molecule called flavin adenine dinucleotide (FAD) that, unlike the rest of the protein, absorbs blue light. Embedded among the 500 or so amino acids that make up a typical cryptochrome is a roughly linear chain of three or four tryptophan amino acids stretching from the FAD out to the surface of the protein. Immediately after the FAD absorbs a blue photon, an electron from the nearest tryptophan hops onto the flavin portion of the FAD. The first tryptophan then attracts an electron from the second tryptophan and so on. In this way, the tryptophan chain behaves like a molecular wire. The net result is a radical pair made of a negatively charged FAD radical in the center of the protein and, two nanometers away, a positively charged tryptophan radical at the surface of the protein.

In 2012 one of us (Hore), working with colleagues at Oxford, carried out experiments to test the suitability of cryptochrome as a magnetic sensor. The study used cryptochrome-1, a protein found in *Arabidopsis thaliana,* the plant in which cryptochromes had been discovered 20 years earlier. Using short laser pulses to produce radical pairs inside the purified proteins, we found that we could fine-tune their subsequent reactions by applying magnetic fields. This was all very encouraging, but, of course, plants don't migrate.

We had to wait almost a decade before we could make similar measurements on a cryptochrome from a migratory bird. The first challenge was to decide which of the six bird cryptochromes to look at. We chose cryptochrome-4a (Cry4a), partly because it binds FAD much more strongly than do some of its siblings, and if there is no FAD in the protein, there will be no radical pairs and no magnetic sensitivity. Experiments in Oldenburg also showed that the levels of Cry4a in migratory birds are higher during the spring and autumn migratory seasons than they are during winter and summer when the birds do not migrate. Computer simulations performed by Ilia Solov'yov in Oldenburg showed that European Robin Cry4a has a chain of four tryptophans—one more than the Cry1 from *Arabidopsis.* Naturally, we wondered whether the extended chain had evolved to optimize magnetic sensing in migratory birds.

Our next challenge was to get large amounts of highly pure robin Cry4a. Jingjing Xu, a Ph.D. student in Mouritsen's lab, solved it. After optimizing the experimental conditions, she was able to use bacterial cell cultures to produce samples of the protein with the FAD correctly bound. She also prepared versions of the protein in which each of the four tryptophans was replaced, one at a time, by a different amino acid so as to block electron hopping at each of the four positions along the chain. Working with these alternative

Adrian Coleman/Getty Images; Imogen Warren/Getty Images (*top* and *bottom*)

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versions of the protein would allow us to test whether the electrons are really jumping all the way along the tryptophan chain.

We shipped these samples—the first purified cryptochromes from any migratory animal—to Oxford, where Timmel and her husband, Stuart Mackenzie, studied them using the sensitive laser-based techniques they had developed specifically for that purpose. Their research groups found that both the third and fourth tryptophan radicals at the end of the chain are magnetically sensitive when paired with the FAD radical. We suspect that the tryptophans work cooperatively for efficient magnetic sensing, biochemical signaling and direction finding. We also speculate that the presence of the fourth tryptophan might enhance the initial steps of signal transduction, the process by which nerve impulses encoding the magnetic field direction are generated and ultimately sent along the optic nerve to the brain. We are currently conducting experiments to identify the proteins that interact with Cry4a.

One more cryptochrome finding deserves mention here. We compared robin Cry4a with the extremely similar Cry4a proteins from two nonmigratory birds, pigeons and chickens. The robin protein had the largest magnetic sensitivity, hinting that evolution might have optimized robin Cry4a for navigation.

OPEN QUESTIONS

ALTHOUGH THESE EXPERIMENTS confirm that Cry4a has some of the properties required of a magnetoreceptor, we are still a long way from proving how migratory birds perceive Earth's magnetic field lines. One crucial next step is to determine whether radical pairs actually form in the eyes of migratory birds.

The most promising way to test for radical pairs inside the birds' eyes was inspired by the work of chemists and physicists who, in the 1980s, showed that fluctuating magnetic fields alter the way radical-pair reactions respond to static magnetic fields. Their work predicted that a weak radio-frequency electromagnetic field, fluctuating with the same frequencies as the "singlet-triplet waltz," might interfere with the birds' ability to use their magnetic compass. Thorsten Ritz of the University of California, Irvine, and his colleagues were the first to confirm this prediction in 2004.

In 2007 Mouritsen began similar behavioral experiments in his lab in Oldenburg—with intriguingly different results. During the spring and fall, birds that travel between nesting and wintering grounds exhibit a behavior called *Zugunruhe,* or migratory restlessness, as if they are anxious to get on their way. When caged, these birds usually use their magnetic compass to instinctively orient themselves in the direction in which they would fly in the wild. Mouritsen found that European Robins tested in wooden huts on his university's campus were unable to orient using their magnetic compass. He suspected that weak radio-frequency noise (sometimes called electrosmog) generated by electrical equipment in the nearby labs was interfering with the birds' magnetic compass.

To confirm that electrosmog was the source of the problem, Mouritsen and his team lined the huts with aluminum sheets to block the stray radio frequencies. On nights when the shields were grounded and functioned properly, the birds oriented well in Earth's magnetic field. On nights when the grounding was disconnected, the birds jumped in random directions. When tested in an unshielded wooden shelter typically used for horses some kilometers outside the city and well away from electrical equipment, the same birds had no trouble detecting the direction of the magnetic field.

These results are significant on several fronts. If the radio-frequency fields affect the magnetic sensor and not, say, some component of the signaling pathway that carries nerve impulses to the brain, then they provide compelling evidence that a radical-pair mechanism underpins the bird's magnetic compass. The main competing hypothesis, for which there is currently much less support, proposes that magnetic iron–containing minerals are the sensors. Any such particles that were large enough to align like a compass needle in Earth's magnetic field would be far too big to rotate in a much weaker field that reversed its direction millions of times per second. Furthermore, the radio-frequency fields that upset the birds' magnetic orientation are astonishingly weak, and we don't yet understand exactly how they could corrupt the directional information available from the much stronger magnetic field of Earth.

It is also remarkable that the birds in the Oldenburg lab were disoriented much more effectively by broadband radio-frequency noise (randomly fluctuating magnetic fields with a range of frequencies) than by the single-frequency fields mostly used by Ritz and his collaborators. We hope that by subjecting migratory songbirds to bands of radio-frequency noise with different frequencies we will be able to determine whether the sensors really are FAD-tryptophan radical pairs or whether, as some other investigators have suggested, another radical pair might be involved.

Many questions about the birds' magnetic compass remain, including whether the magnetic field effects on robin Cry4a observed in vitro also exist in vivo. We also want to see whether migratory birds with genetically suppressed Cry4a production are prevented from orienting using their magnetic compass. If we can prove that a radical-pair mechanism is behind the magnetic sense in vivo, then we will have shown that a biological sensory system can respond to stimuli several million times weaker than previously thought possible. This insight would enhance our understanding of biological sensing and provide new ideas for artificial sensors.

Working to gain a full understanding of the inner navigation systems of migratory birds is not merely an intellectual pursuit. One consequence of the enormous distances migratory birds travel is that they face more acute threats to their survival than most species that breed and overwinter in the same place. It is more difficult to protect them from the harmful effects of human activity, habitat destruction and climate change. Relocating migratory individuals away from damaged habitats is rarely successful because the birds tend to instinctively return to those unlivable locales. We hope that by providing new and more mechanistic insights into the ways in which these extraordinary navigators find their way, conservationists will have a better chance of "tricking" migrants into believing that a safer location really is their new home.

When you next see a small songbird, pause for a moment to consider that it might recently have flown thousands of kilometers, navigating with great skill using a brain weighing no more than a gram. The fact that quantum spin dynamics may have played a crucial part in its journey only compounds the awe and wonder with which we should regard these extraordinary creatures. SA

Peter J. Hore is a chemist at the University of Oxford. He works on the biophysical chemistry of electron and nuclear spins and their effects on processes such as the mechanisms of animal magnetoreception.

Henrik Mouritsen is a biologist at the University of Oldenburg in Germany. He studies the mechanisms of orientation and navigation in many different animals with an emphasis on night-migrating songbirds.

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THE FRONT FACE of the Thwaites Ice Shelf towers up to 40 meters above the sea. The slab of floating ice is rapidly weakening.

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The Coming Collapse

Two expeditions to Antarctica's Thwaites Ice Shelf have revealed that it could splinter apart in less than a decade—allowing a vast glacier behind it to slide into the sea

By Douglas Fox

Photograph by Elizabeth Rush

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ON DECEMBER 26, 2019, ERIN PETTIT TRUDGED ACROSS A PLAIN OF GLARING snow and ice, dragging an ice-penetrating radar unit the size of a large suitcase on a red plastic sled behind her. The brittle snow crunched like cornflakes underneath her boots—evidence that it had recently melted and refrozen following a series of warm summer days. Pettit was surveying a part of Antarctica where, until several days before, no other human had ever stepped. A row of red and green nylon flags, flapping in the wind on bamboo poles, extended into the distance, marking a safe route free of hidden, deadly crevasses. The Thwaites Ice Shelf appeared healthy on the surface. But if that were the case, Pettit wouldn't have been there.

Pettit was studying defects within the ice, akin to hidden cracks in an enormous dam, that will determine when the ice shelf might crumble. When it does, the rest of the West Antarctic Ice Sheet behind it could flow right into the ocean, pushing up sea levels around the planet, flooding coastal cities worldwide.

From a distance, the ice shelf looks flat, but as Pettit walked she saw the guide flags ahead of her rise and fall against the horizon—a sign that she was walking across an undulating surface. To Pettit, a glaciologist at Oregon State University in Corvallis, this was significant. It meant that the ice's underside was a rolling landscape—not what anyone expected. In satellite images, the center of the ice shelf looks stable. But it isn't, Pettit says: "There are five or six different ways this thing could fall apart."

The Thwaites Ice Shelf begins where the massive Thwaites Glacier meets the West Antarctic coast. The shelf is a floating slab of ice, several hundred meters thick, extending roughly 50 kilometers into the Southern Ocean, covering between 800 and 1,000 square kilometers. For the past 20 years, as the planet has warmed, scientists using satellites and aerial surveys have been watching the Thwaites Ice Shelf deteriorate. The decline has caused widespread alarm because experts have long viewed the Thwaites Glacier as the most vulnerable part of the larger West Antarctic Ice Sheet. The ice shelf acts as a dam, slowing its parent glacier's flow into the ocean. If the shelf were to fall apart, the glacier's slide into the sea would greatly accelerate. The Thwaites Glacier itself holds enough ice to raise the global sea level by 65 centimeters (about two feet). The loss of the Thwaites Glacier would in turn destabilize much of the rest of the West Antarctic Ice Sheet, with enough ice to raise sea levels by 3.2 meters—more than 10 feet.

Even the most optimistic greenhouse gas emissions scenarios indicate that by 2050 humanity will likely be locked in to at least two meters of sea-level rise in the coming centuries. That will put the homes of at least 10 million people in the U.S. below the high tide line. If the Thwaites Glacier collapses and destabilizes the heart of West Antarctica, then sea-level rise jumps to five meters, placing the homes of at least 20 million U.S. people and another 50 million to 100 million people worldwide below high tide. Although Sacramento, Calif., is not the first city that comes to mind when imagining sea-level rise, it would lose 50 percent of its homes as ocean water pushes 80 kilometers inland through low-lying river deltas. The fate of thousands of coastal towns worldwide hangs on events unfolding in Antarctica right now.

Since 1992 the glacier has hemorrhaged a trillion tons of ice. It is currently losing an additional 75 billion tons of ice every year, and the rate is increasing. What happens next, however, depends on processes that can't be studied from the air—flaws within the shelf that could break it apart, accelerating the glacier's demise. That's why, in 2018, the British National Environmental Research Council and the U.S. National Science Foundation launched a $50-million effort called the International Thwaites Glacier Collaboration to study the glacier and its ice shelf up close.

The collaboration involved eight research teams, including one that reported in September 2022 that the glacier was retreating faster than had been predicted just a few years ago. Two of the teams visited the Thwaites Eastern Ice Shelf between November 2019 and January 2020. Pettit's team examined the central part of the shelf, looking at structural defects and ocean currents underneath. I accompanied her team as an embedded journalist, earning my keep with unskilled labor, much of it involving a snow

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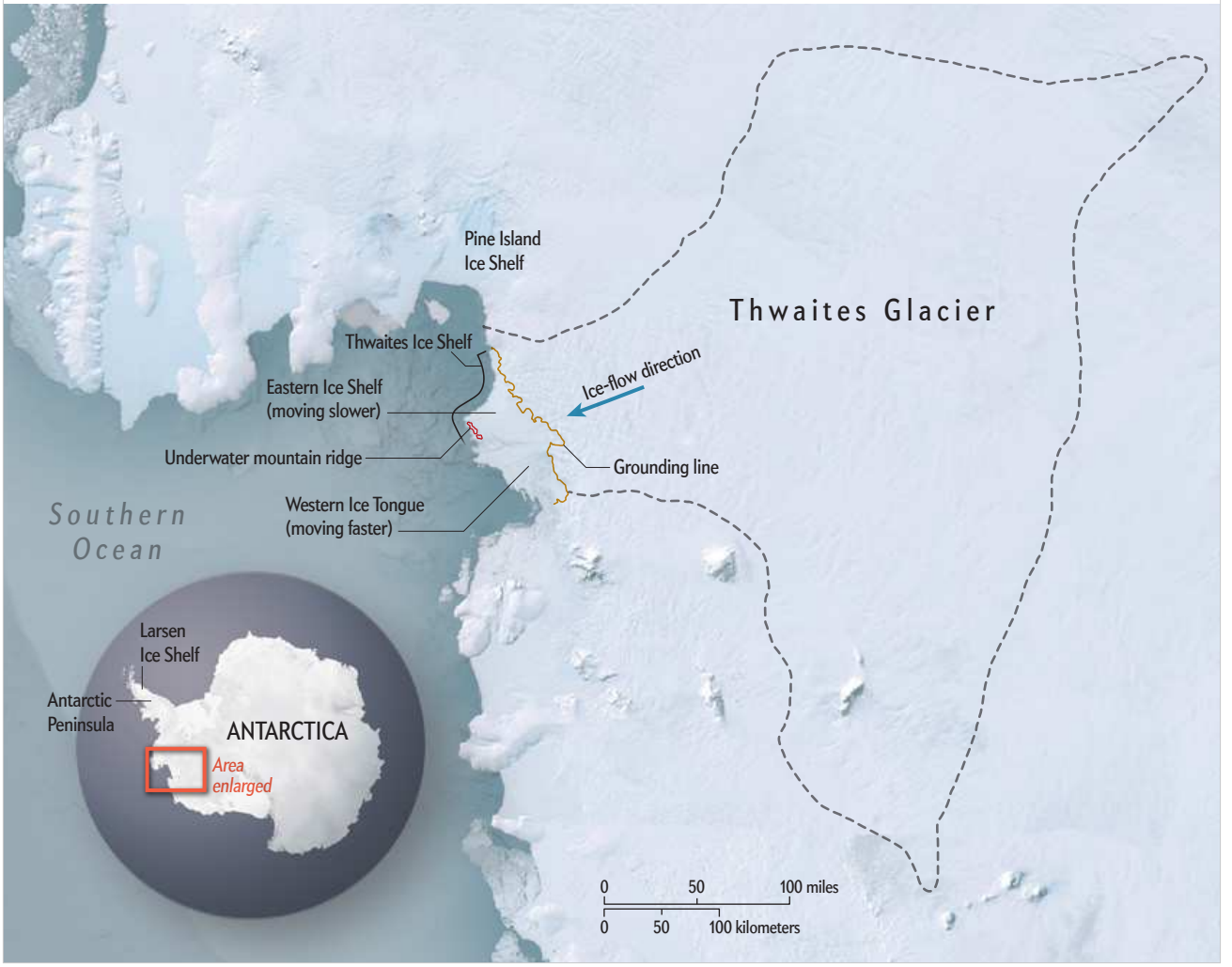
Thwaites Glacier, Ready to Flow

Antarctica's Thwaites Glacier, about the size of Nebraska, slowly flows into the Southern Ocean. It is held back by the Thwaites Ice Shelf, which is braced by the seafloor along the grounding line and by underwater mountain peaks at sea. The shelf is fragmenting, however, speeding the glacier's demise, which would raise global sea level by 65 centimeters (about two feet).



shovel. Another team investigated the back edge of the ice shelf along the continent's submerged shore, sending a remotely operated submarine down a narrow hole to explore a crucial environment hidden under 600 meters of ice, where the shelf is melting most quickly. The results paint a worrisome picture. The ice shelf "is potentially going to go a lot faster than we expected," Pettit says.

ANTARCTICA'S ICE SHEET HAS CONSISTENTLY SURPRISED those who study it. In February 1958 researchers in West Antarctica, 700 kilometers inland from the coastline, drilled four meters into the snow, lowered in 450 grams of explosives and detonated them with a muffled *fuff* that sprayed snow in the air. Geophones sitting facedown on the ice recorded the sound waves that reflected off the hard ground far below. By measuring the return time, Charles Bentley, then a graduate student at Columbia University, made a shocking discovery: the ice in this location was more than 4,000 meters thick—several times thicker than anyone expected—and rested on an old ocean floor 2,500 meters below sea level.

By the 1970s researchers were flying ice-penetrating radar in airplanes that crisscrossed the region. The scattered surveys confirmed that the West Antarctic Ice Sheet sits in a broad basin, deepest toward the center, with large glaciers spilling into the sea through gaps in the basin's outer rim. Even as scientists testified to Congress in the late 1970s about carbon dioxide and the dangers of global warming, most of them didn't think that Antarctica would lose its ice anytime soon. But in 1978 John Mercer, a glaciologist at the Ohio State University, sounded the alarm that West Antarctica represented "a threat of disaster." If the ice sheet lost the shelves separating it from the sea, it might crumble far

Map by Mapping Specialists

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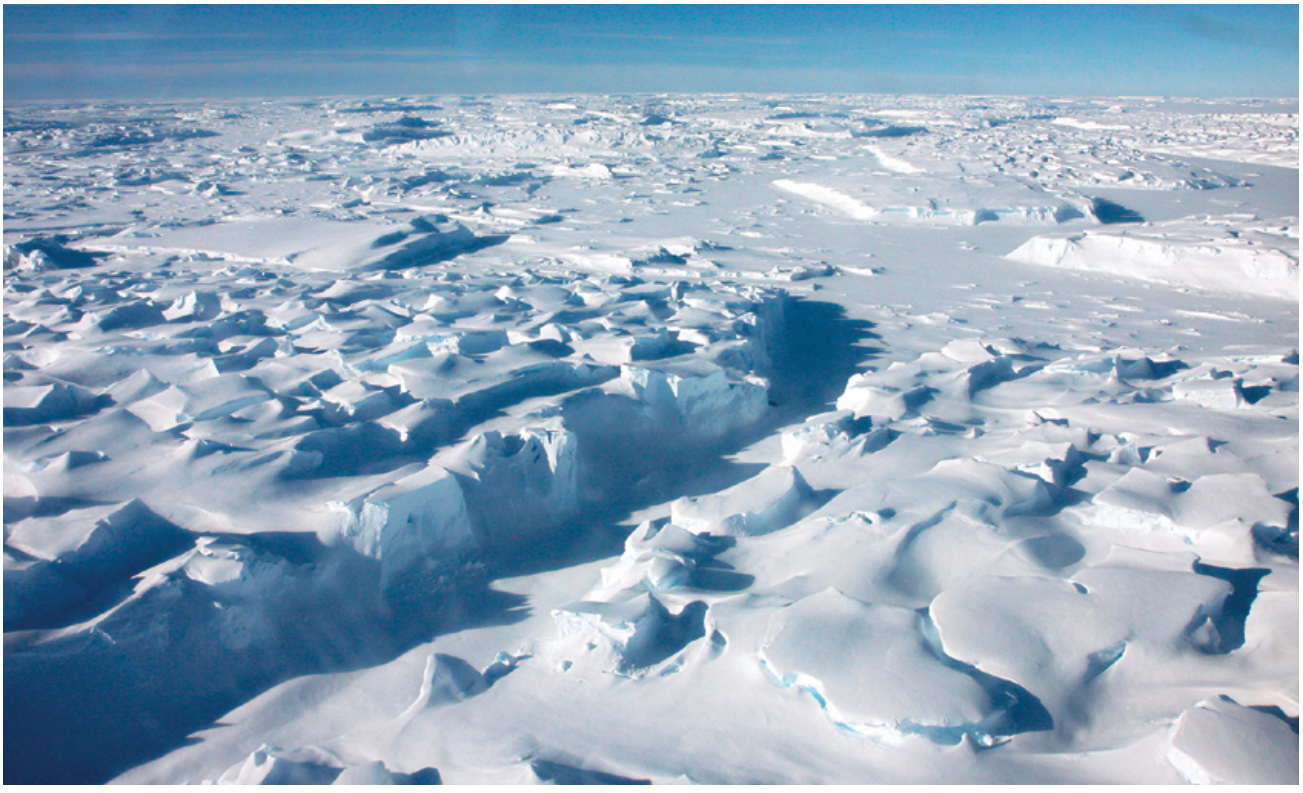

THE WESTERN ICE TONGUE of Thwaites has splintered into hundreds of icebergs, which look like raised plateaus, interspersed with sea ice perhaps a meter thick, all covered in snow.

Douglas Fox

more quickly than people imagined. Three years later Terry Hughes, a glaciologist at the University of Maine, called out two specific coastal glaciers—Thwaites and Pine Island—as "the weak underbelly" where the collapse of the ice sheet would most likely begin. A pair of papers published in 1998 and 2001 by Eric Rignot, a glaciologist at NASA's Jet Propulsion Laboratory, showed that these two glaciers were indeed thinning, melting from beneath, allowing ocean water to intrude farther inland under the ice.

Additional aerial surveys since then have shown that the Thwaites Glacier is especially troubling. The ground underneath the glacier is a relentless slope that drops deeper as it moves inland from the outer, seaward edge, allowing ocean water to slide under the glacier, melting it from below. As the ice thins, losing weight, it is also expected to lift off the bed and float on the intruding warm, dense water, allowing the water to penetrate even farther—eventually reaching the 2,500-meter trench at the heart of the continent. If that happens, "you're going to unload the West Antarctic Ice Sheet," says Ted Scambos, a glaciologist at the University of Colorado Boulder, who traveled with Pettit's team in 2019–2020.

The glacier flows into the sea in two arms that move at different speeds. The "fast arm" on its western side is a fragile, floating "ice tongue." In satellite images it resembles a shattered windshield, composed of hundreds of icebergs a kilometer or two across drifting into the ocean. The "slow arm," on the glacier's eastern side, is a smaller ice shelf that for years seemed more stable. The front edge butts into a submarine mountain ridge 40 kilometers off the coast. This ridge acts like a doorstop, creating back pressure that holds the ice shelf together.

Pettit and her team chose the mountain-buttressed eastern shelf for their expedition. In satellite images, the shelf's central region appeared relatively stable, its surface smooth enough for small ski-mounted planes to land. A pair of mountaineers could scout for hidden crevasses and establish safe routes, allowing the team to move around freely. Pettit worried that visiting an apparently undamaged part of the ice shelf might limit their opportunity to learn something new. She didn't need to worry.

ANTARCTIC FIELDWORK REQUIRES SENDING TONS OF fuel, food and survival gear ahead of time. The field team has to be supported by layers of transport, workers and staging camps. All told, the Thwaites research expeditions required several hundred thousand kilograms of equipment and supplies delivered by ships, planes and convoys of tractors towing sleds across hundreds of kilometers of ice that had been searched ahead of time for crevasses. The British Antarctic Survey and the U.S. Antarctic Program staged some of that gear a year or two in advance. But in Antarctica, even this kind of preparation isn't enough to avoid complications.

In September 2019, two months before I joined Pettit's team as they departed for the frozen continent, they received new satellite images showing two new rifts in the ice shelf. These "daggers" originated where the ice collides with the undersea mountain; the rifts had surged inward toward the coast, to within five kilometers of our planned destination. Expedition leaders worried that one of these rifts could rip through the camp, but the team decided to press forward, with a colleague back home track-

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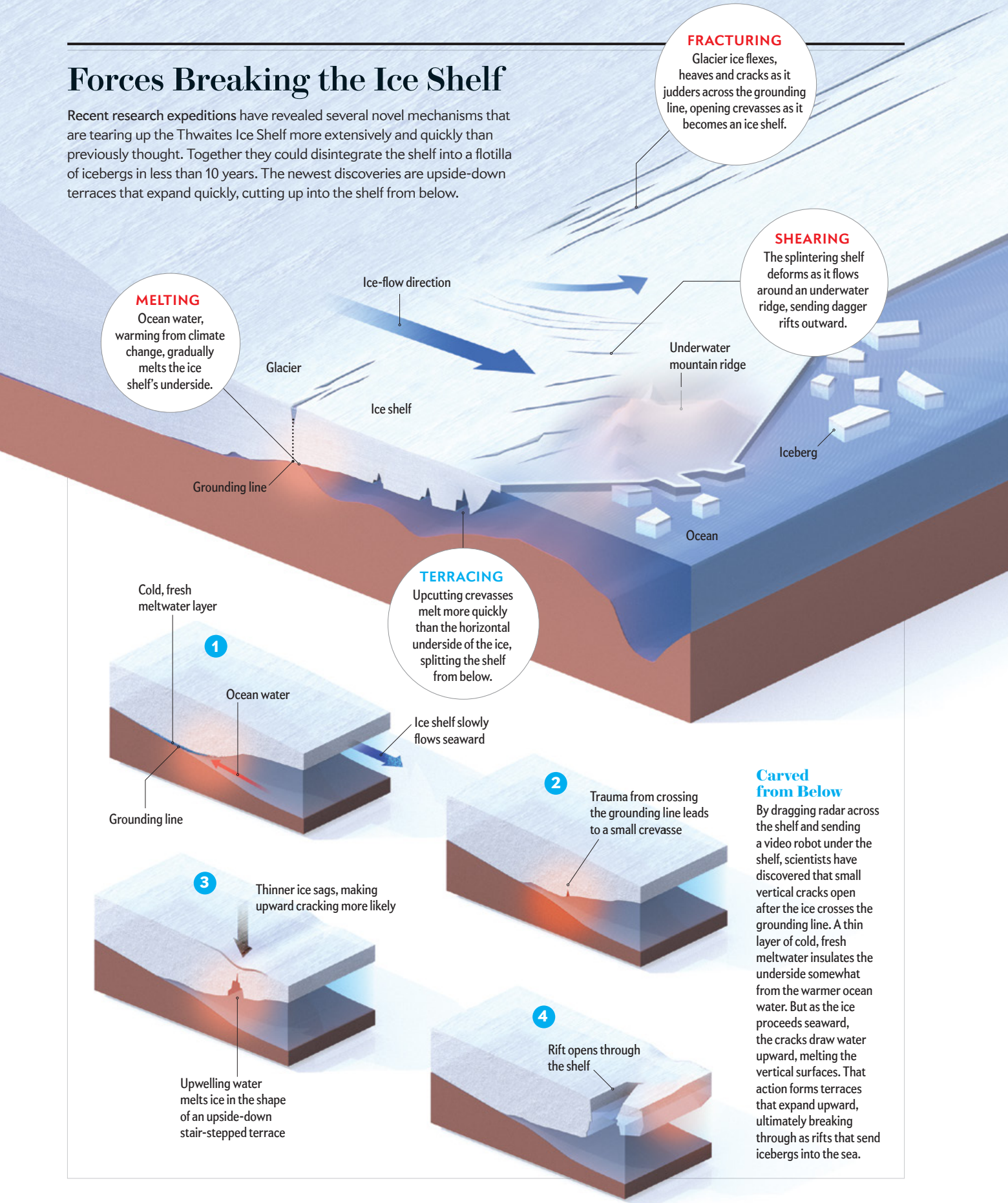
Forces Breaking the Ice Shelf

Recent research expeditions have revealed several novel mechanisms that are tearing up the Thwaites Ice Shelf more extensively and quickly than previously thought. Together they could disintegrate the shelf into a flotilla of icebergs in less than 10 years. The newest discoveries are upside-down terraces that expand quickly, cutting up into the shelf from below.


FRACTURING
Glacier ice flexes, heaves and cracks as it judders across the grounding line, opening crevasses as it becomes an ice shelf.
SHEARING
The splintering shelf deforms as it flows around an underwater ridge, sending dagger rifts outward.
MELTING
Ocean water, warming from climate change, gradually melts the ice shelf's underside.
Ice-flow direction
Glacier
Ice shelf
Underwater mountain ridge
Iceberg
Grounding line
Ocean
TERRACING
Upcutting crevasses melt more quickly than the horizontal underside of the ice, splitting the shelf from below.
Cold, fresh meltwater layer
1
Ocean water
Ice shelf slowly flows seaward
Grounding line
2
Trauma from crossing the grounding line leads to a small crevasse
3
Thinner ice sags, making upward cracking more likely
Upwelling water melts ice in the shape of an upside-down stair-stepped terrace
4
Rift opens through the shelf

Carved from Below

By dragging radar across the shelf and sending a video robot under the shelf, scientists have discovered that small vertical cracks open after the ice crosses the grounding line. A thin layer of cold, fresh meltwater insulates the underside somewhat from the warmer ocean water. But as the ice proceeds seaward, the cracks draw water upward, melting the vertical surfaces. That action forms terraces that expand upward, ultimately breaking through as rifts that send icebergs into the sea.

Graphic by Violet Frances for Bryan Christie Design

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ing the rifts via satellite. After a series of storms delayed the expedition by a few weeks, we reached the Thwaites Eastern Ice Shelf in mid-December 2019. We assembled a row of tents, protected from the constant easterly winds by walls of snow blocks shoveled and handsawed from the landscape, and set up gear for what would be a month of arduous work to come.

The first couple of days were relatively warm. Our boots plunged deeply into the slushy snow, and puddles of meltwater pooled up along the tents. A series of giant ice cliffs, eight kilometers away, were visible to the south. Those upheavals marked the zone where the ice cracked and flexed as it transitioned from a grounded glacier into a floating ice shelf.

As the weather cooled and the snow hardened, Pettit made her first long walks, dragging her radar along preplanned lines. The radar provided two-dimensional profiles of the ice shelf's internal layers, like the slices of a hospital MRI scan. Those first glimpses proved far more interesting than Pettit expected.

Her radar showed that layers in the top 25 meters of the shelf were smooth and mostly flat, but below that they suddenly turned jagged. Pettit speculated that the jagged layers had been part of the ice when it juddered across the rocky coastline bed and started to float seaward, perhaps 15 years before; they were forever imprinted with the trauma of that transition. The smooth layers represented snow that had fallen on top since then, when the ice was afloat.

More surprising, Pettit found that the shelf's underside—a place that human eyes had never seen—looked strangely ordered, as if it had somehow been sculpted intentionally. The underside was corrugated with a series of trenches that ran perpendicular to the direction of ice flow, like waves offshore from a beach. Each trench was 500 to 700 meters wide and cut as far as 50 meters up into the ice, the height of a 12-story building. "These things are huge," Pettit told me. Oddest of all, the trench walls weren't smooth, as one might expect of melting ice. They were stair-stepped terraces, with a series of vertical walls each five to eight meters tall, like the sides of an open-pit mine. "We don't know what these stepped things are," she said.

These stair-stepped trenches had escaped detection in previous surveys. Airborne radar measurements are taken from planes moving at least 150 kilometers per hour, so each reading is an average over a long swath of ice. Pettit dragged her radar at a stately three kilometers per hour, allowing her to capture a much finer-grained picture.

As Pettit was getting her first look at the strange terraced structures, her colleagues were starting to see hints of another unexpected observation: the bottom of the ice was not melting the way they expected. On January 2, I wolfed down a breakfast of dehydrated porridge with Christian Wild, a postdoctoral scholar who works with Pettit. He and I then drove a snowmobile out into a frigid snowfall. The sound of the engine was muffled, and the wan light seemed to seep in from all directions, leaving no shadows, no texture and no hint of the approaching bumps that we trundled over. We steered along our GPS line, with just enough visibility to see each new flag appear silently into view, then dissolve behind us in a gentle slurry of snowflakes.

At a series of stops, Wild used high-precision radar to measure the thickness of the ice shelf, accurate to a few millimeters. He had already measured the same points a week earlier. Because satellite estimates suggested the ice shelf was thinning an average of two or three meters per year, he expected to find the ice three to six centimeters thinner than the week before. To his astonishment, he saw almost no thinning. "It doesn't make any sense," he said toward the end of a long day.

Back at camp, other team members prepared to measure the temperature of the ocean currents flowing under the ice shelf. Over several days they tossed 6,000 kilograms of hard snow, one block at a time, into a canvas-sided tank the size of a large hot tub. They melted the snow and heated the water, then used it to make a hole as wide as a dinner plate 250 meters down through the shelf. Scambos lowered a string of sensors through this hole into the ocean water below. For the next year or two this sensor station, powered in part by solar panels on a small steel tower, would measure the water temperature, salinity and currents.

Initial readings showed that warm, dense water was indeed flowing under the shelf. At two degrees above freezing, it should be "enough to melt many meters of ice over the course of a year," Scambos said. But the ice wasn't feeling the heat. A layer of cold water sat up against the shelf's underside. Because that water came from the melting of glacial ice (which itself comes from snow), it contained little salt, so it was buoyant, hugging the bottom of the shelf and shielding it from the warmer, saltier water below.

ERIN PETTIT pulls an ice-penetrating radar (*above*) that can peer down into the ice shelf. She walked for many kilometers beyond base camp, where tents were protected from constant wind by walls made of handsawed snow blocks (*right*).

Douglas Fox

By the end of the expedition Pettit's team had encountered a series of revelations that defied previous views of the ice shelf. First, its underside was eroded with deep trenches, and the slopes of those trenches were organized into stair-stepped terraces. Second, the ice didn't appear to be thinning at the points Wild measured, which disagreed with satellite surveys. Finally, the underside of the shelf didn't seem to be feeling heat from the deep ocean, because it was insulated by a layer of cold, buoyant water. This set of findings

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was difficult to explain, but another research expedition, operating not far away, would help make sense of the surprises.

Eight kilometers southeast of Pettit's camp, the other group of scientists was getting a first look at the ice shelf's grounding line—the long contour of ground where ice lifts off the land and floats on the sea. In this hidden place, scientists believed the underside of the ice was melting most quickly.

On January 11, 2020, researchers at the camp lowered a black-and-yellow cylindrical vehicle, as wide as two hands and 3.5 meters long, by cable into a narrow hole in the ice. Engineers led by Britney Schmidt, a planetary and polar scientist now at Cornell University (then at the Georgia Institute of Technology), had spent eight years developing this remotely operated vehicle, called Icefin. They had driven it under sea ice more than a meter thick and under the edges of two small ice shelves, where it could be winched out by cable if it got stuck. But they had never lowered this precious object through such a massive slab.

Douglas Fox

Schmidt sees Icefin as a prototype of a probe that will one day explore vast bodies of water in the outer solar system, hidden underneath 10 or 20 kilometers of ice on Jupiter's and Saturn's moons. In Antarctica, Icefin would measure the ocean temperatures, currents and rates of melting under the ice. Perhaps more important, its video cameras and sonar would allow the researchers to visually explore this remote environment. Schmidt wasn't looking to validate any of Pettit's observations per se, but the two researchers were working relatively close by, on the same ice shelf, so serendipity could play a role.

After descending through the 600 meters of ice, the vehicle emerged into a layer of ocean water only 50 meters deep. Schmidt, sitting in a nearby tent, steered Icefin with her thumbs on the controller of a PlayStation 4 console. The glassy ceiling of the ice's underside scrolled past on her video monitor as Icefin glided along, sending video up its fiber-optic tether. For eight hours Schmidt guided the vehicle as far as two kilometers from the borehole, into narrow spaces where less than a meter of water separated the ice above from the gravelly, gray-brown seafloor below. This was newly exposed seafloor; the thinning ice had pulled away from it only a few days or weeks before. An occasional fish or shrimp drifted by.

In most places, the currents were sluggish, and close to the ice the water was stratified. As the vehicle approached the grounding line, the water near the ice was at most one degree Celsius above freezing, even though warmer water lay only a few meters away. Icefin's measurements suggested that the underside of the ice was melting at a modest rate of about two meters a year. In some places, meltwater had refrozen onto the bottom of the glacier, revealing a distinct layer of crystal-clear ice, several centimeters thick. Satellite observations had shown this region rapidly thinning, so the findings were at odds with the team's expectations, says Keith Nicholls, an oceanographer at the British Antarctic Survey, who co-led the research at the camp. The overall lack of melting was puzzling, he said: "Extraordinary, really."

As Icefin swam around, it occasionally encountered a clue that would help explain not only these unanticipated observations but also what Pettit's team had found. Cruising slowly along the shelf's fairly flat underside, Icefin came across a vertical wall cut up into the ice—a stair-stepped terrace like Pettit had seen in her radar traces. And the ice on the terrace walls seemed to be melting far more quickly than the surrounding horizontal underside. In the video, there were blurry ripples in the water, where Icefin's spotlight refracted through gushing eddies of saltwater and freshwater swirling together. Icefin also frequently found dark cracks gaping in the ice—basal crevasses as wide as 100 meters. Schmidt steered Icefin up into several of the crevasses, and there again, she found the water swirling and blurry, suggesting the ice may have been melting quickly.

At the December 2021 American Geophysical Union (AGU) meeting in New Orleans, Schmidt's team presented a careful analysis of Icefin's data, confirming that the vertical ice surfaces are playing a pivotal role in the demise of the Thwaites Ice Shelf. Peter Washam, a research scientist at Cornell, reported that the terrace walls were melting five times more quickly than horizontal

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ice surfaces, losing 10 or more meters of ice a year. The crevasse walls were melting even more quickly—up to 10 times as fast, losing 20 meters of ice a year. Washam noted that the water currents became turbulent as they encountered these steep surfaces, and this brought water into contact with the ice in ways that more efficiently melted it.

The vertical steps may originate from subtle ups and downs present on the ice's underside when it first pulls up from the bed along the grounding line. The ice might fracture and melt more quickly in these uneven spots, steepening the slope—which increases the melt rate, causing the slope to steepen even more, until it forms a terrace wall that is nearly vertical. As ice melts from these vertical surfaces, the terrace walls migrate horizontally, Scambos says. A basal crevasse that is 10 meters across might widen to 30 or even 50 meters within a year. The melting of the Thwaites Ice Shelf's underside isn't a uniform process; it is highly localized, directed by the topography interacting with currents.

If most of the melt is happening on the vertical ice faces, that could help explain why Wild saw no signs of thinning in many of the places he measured. After returning home in 2020, Pettit plotted Wild's points on her radar survey lines showing the terrace walls. In each case, Wild's measurements fell some distance from the closest wall, in a spot where the ice base was horizontal and so maybe not melting much. This isn't unusual, Pettit says, because the walls are spaced far enough apart that Wild was unlikely to hit one by chance. The instrument station that Scambos left behind also seems to be located some distance from the nearest wall; it, too, has shown very little ice thinning.

If the vertical walls are melting quickly, they should also be migrating horizontally across the ice base, Pettit says. At some point, one of those vertical faces will sweep past Scambos's instrument station, "and we will see a huge amount of melt in a short time," she says—perhaps eight meters in a week. "If we see that, it would be supercool."

Schmidt's observations may also explain another feature of the terraced trenches Pettit saw near camp. After Pettit returned home, she examined her radar traces and noticed something peculiar: in the highest segment of a trench, she often saw a stack of inverted U-shaped radar reflections—the classic signature of a crevasse penetrating up into the ceiling. This might occur because the thinner ice over a trench sags like a flimsy bridge; as the ice flexes downward, its bulging belly cracks open. This newly formed basal crevasse may pull in warmer water from below. That would cause the walls of the crevasse to melt and migrate outward, widening until its ceiling is broad enough that it also sags and cracks open—a repeating cycle that could drive cracks ever farther into the ice above.

The massive terraced trenches may have started out as individual basal crevasses, like the ones Schmidt saw eight kilometers upstream at the grounding zone. When Elisabeth Clyne, then a graduate student at Pennsylvania State University, examined radar traces from around the grounding zone, she saw signs that as crevasses moved farther out toward the sea, at roughly 600 meters a year, they were already starting to grow wider and taller through cycles of melting, sagging and cracking. She reported her analysis at the 2021 AGU meeting in New Orleans. Pettit suspects that these trenches may eventually penetrate all the way up through the shelf or at least cut far enough up through the ice that the shelf becomes prone to breaking from other stresses. This process could splinter the shelf into an unsteady mass of giant, shifting shards that will no longer stabilize one of Antarctica's largest glaciers.

ALTHOUGH THWAITES'S WESTERN ICE TONGUE LOST 80 PERCENT of its area in the past 25 years, the eastern shelf shrunk only about 15 percent. Its seaward snout remains pressed against the undersea mountain ridge, which crests roughly 400 meters underneath the ocean's surface. The pressure from this "pinning

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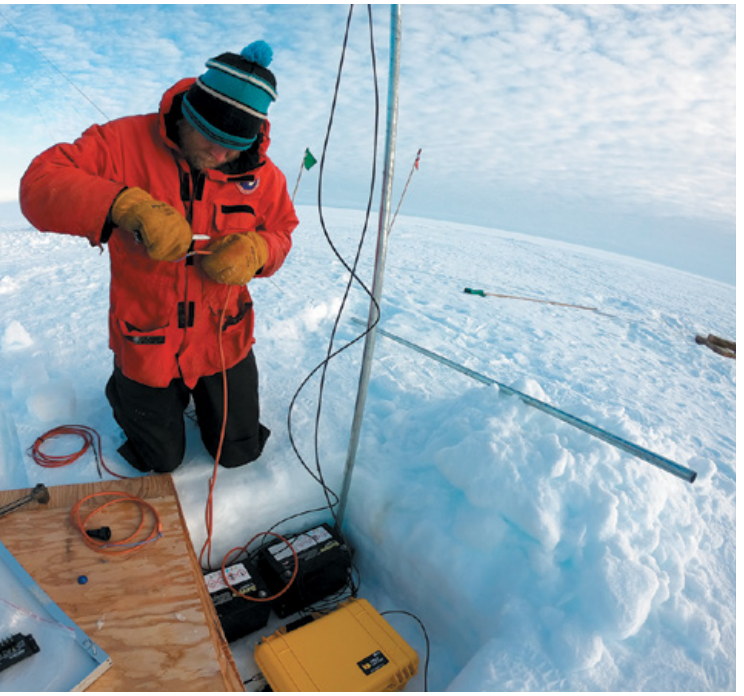

CHRISTIAN WILD prepares a high-precision radar (*left*) to measure ice-shelf thickness to within a few millimeters. Martin Truffer sets up an instrument station (*above*) that would record the shelf's advancement and upheaval for two years after researchers left Thwaites.

Douglas Fox

point" holds the ice together, but the status quo may not last much longer.

In February 2022 Wild published an analysis of satellite measurements showing that the front face of the ice in contact with the underwater mountain ridge is thinning by 30 centimeters a year. At that rate, it will lift off the top of the mountains in the next 10 years. Wild expects that when this happens, the eastern ice shelf will rapidly "disaggregate" into a flotilla of icebergs. But it may meet its end even sooner. If focused terrace melting is driving cracks upward through the ice, that could amplify the mechanical stresses that are already tearing at the shelf.

Massive splintering is already happening just upstream of the mountain ridge. Over the past decade the ice there has fragmented into a logjam of long shards held together only by pressure and friction. A series of satellite images, stitched into an animation by Andrew Fleming of the British Antarctic Survey, shows that these shards are sliding past one another with increasing ease. As a result, the splintering shelf is starting to deform and flow around the mountain ridge more quickly and in new directions, like a river that parts as it flows around a boulder. The mountain—once a stabilizing buttress—is now acting as a wedge, sending several "dagger" rifts surging back toward land. These are the same rifts that we saw via satellite just before we left for Antarctica in 2019.

"The thing is falling apart," says Karen Alley, a glaciologist at the University of Manitoba in Winnipeg, who published an analysis of these ice-flow patterns in November 2021. Even if the ice disconnects from the mountain ridge more slowly than expected, another scenario could doom the shelf. Those dagger rifts could keep lengthening until they intersect with the rising trenches advancing seaward from shore. This intersection of structural defects could lead to a shattering of the entire shelf.

In every scenario, the eastern ice shelf will meet a fate similar to the western ice tongue: its constituent shards will disconnect and drift away. Once that happens the eastern trunk of the Thwaites Glacier will break away from its pinning point, and the western trunk could also speed up. "This whole thing is going to go much faster once the ice [shelf] is all cleared out," Scambos predicts.

PETTIT'S TEAM LEFT THWAITES IN LATE JANUARY 2020, but they continued monitoring the shelf's health using solar-powered instruments they lowered into the ocean through holes drilled through the ice. In January 2022 Scambos and Wild returned to our camp site for a few chaotic days to retrieve the data. Antenna and solar towers that once rose seven meters above the ice were mostly buried in hard, icy snow. Scambos, Wild and two other workers used ice-penetrating radar to find the buried instruments. They then chain-sawed narrow pits six meters down into the ice to retrieve the treasured data cards.

In hopes of getting another year of data out of his instruments, Scambos reinforced the steel towers that had been bent like paper clips and reset the modems that had been fried by static discharge during windstorms. Sensors on the towers had detected winds up to 250 kilometers per hour—nearly Category 5 hurricane speeds and twice what Scambos expected.

GPS units from those stations show that in the two and a half years since they were installed, the ice shelf's seaward movement increased from 620 meters a year to 980 meters a year. As Scambos and Wild gazed down from their Twin Otter plane in January 2022, they spotted several new tears in the shelf—three kilometers long and several hundred meters wide—where it lifts off the seafloor. Ragged cliffs of ice tilted 50 meters up into the air, exposing deep layers that had not seen daylight for thousands of years. "I think it's losing contact with everything that used to be bracing it," Scambos says. Not only is the ice shelf separating from its pinning point. As it speeds up, it is also stretching and tearing away from the glacier upstream.

The team was so alarmed that Pettit and Wild decided they would return in December 2022 to install a new instrument station: "BOB," short for Breakup Observer. They hope BOB will survive long enough to record the final throes of the ice shelf as it fractures into shards. It might not take long.

Scambos speculated that as Pettit and Wild camped on the ice shelf in December, they might wake up one morning to find themselves on a free-floating iceberg. "As long as they're not near one of the rifts, they're not even going to know" at first, he says. Any sounds or vibrations from a crevasse breaching the surface from below may be muffled. Subtle clues would gradually alert them. As the iceberg slowly rotated, their handheld GPS would seem to guide them in the wrong direction, and the sun might also move the wrong way. "You're on this giant white lily pad," Scambos says, "and your only reference is that you're used to having the sun in a certain place at a certain time of day." SA

Douglas Fox writes about biology, geology and climate science from California. He wrote the July 2021 article "The Carbon Rocks of Oman," about efforts to turn carbon dioxide into solid minerals.

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THE MYSTERY OF MILKY SEAS

Scientists are beginning to understand an eerie phenomenon that has bewildered seafarers for centuries

By Michelle Nijhuis

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MANY MARINE CREATURES emit light, providing one clue as to why the sea's surface can sometimes appear ghostly white.

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ON JANUARY 30, 1864, THE CONFEDERATE WARSHIP CSS *ALABAMA* entered what its captain described as a "remarkable patch of the sea." The *Alabama,* sailing southwest along the Horn of Africa, was one of several Confederate vessels cruising the world's oceans during the U.S. Civil War, weakening the Union by raiding its merchant ships. Formidable pirates though they were, Captain Raphael Semmes and his crew were spooked by the sea they encountered that January evening. "At about eight P.M., there being no moon, but the sky being clear, and the stars shining brightly, we suddenly passed from the deep blue water in which we had been sailing, into a patch of water so white that it startled me," Semmes recounted in a memoir.

At first he thought that the pale, constant glow indicated a submerged ridge, but a weighted line the crew dropped over the gunwale sank for 600 feet without hitting bottom. "Around the horizon there was a subdued glare, or flush, as though there were a distant illumination going on, whilst overhead there was a lurid, dark sky," Semmes wrote. "The whole face of nature seemed changed, and with but little stretch of the imagination, the *Alabama* might have been conceived to be a phantom ship, lighted up by the sickly and unearthly glare of a phantom sea." The *Alabama* traveled through the eerie water for several hours, finally exiting the patch as abruptly as it had entered it.

Semmes's firsthand description is one of the earliest reliable accounts of such a sea, and it has become a valuable, though inadvertent, contribution to science. Now, after combining dozens of historical reports with state-of-the-art satellite data, researchers are close to solving one of the ocean's most persistent mysteries—its vast, ephemeral displays of ghostly living light.

SILENT DREAD

THE COLD RADIANCE emitted by fireflies, some species of fungi and various sea creatures is called bioluminescence. Although it is one of the oldest subjects of scientific study, it is also among the most elusive. Mentions of animal light appear in ancient poetry and songs from many cultures. In the third century B.C.E., Aristotle noticed that if he struck the surface of the sea with a rod, the water sometimes produced a bright blue flash. Three hundred years later Pliny the Elder described light-emitting species of mollusks, jellyfish and mushrooms, adding that the Black Forest of central Europe was rumored to glow with bioluminescent birds (such rumors, though often repeated, were unfortunately never confirmed).

Around 1370 Egyptian zoologist Al-Damiri included bioluminescent insects in his zoological dictionary. And in 1492, during his fateful approach to the Bahamas, Christopher Columbus observed glimmers of light in the ocean—an occurrence that scientists now surmise was produced by bioluminescent marine worms of the genus *Odontosyllis,* which periodically rise to the water's surface en masse to perform a circular mating "dance." In the late 1800s, after centuries of speculation, scientists confirmed that bioluminescence results from an oxidation reaction between an enzyme and its substrate within animal and plant cells. Basic questions remained, however: no one knew what prompted different organisms to glow or what purpose the light might serve.

Most accounts of bioluminescence, on land and at sea, describe blue-green flashes and gleams, sometimes stimulated by disturbance, as with Aristotle's rod. But reports such as that of Captain Semmes suggested a very different phenomenon. The seawater plied by sailors was suffused with steady white light, not bluish bursts, and the glow often stretched for miles. These "milky seas" were rare enough, and strange enough, that people widely considered them to be tall tales—more plausible than mermaid encounters, perhaps, but just barely so. Herman Melville, in his 1851 epic *Moby-Dick,* por-

Henley Spiers/Minden Pictures *(preceding pages)*

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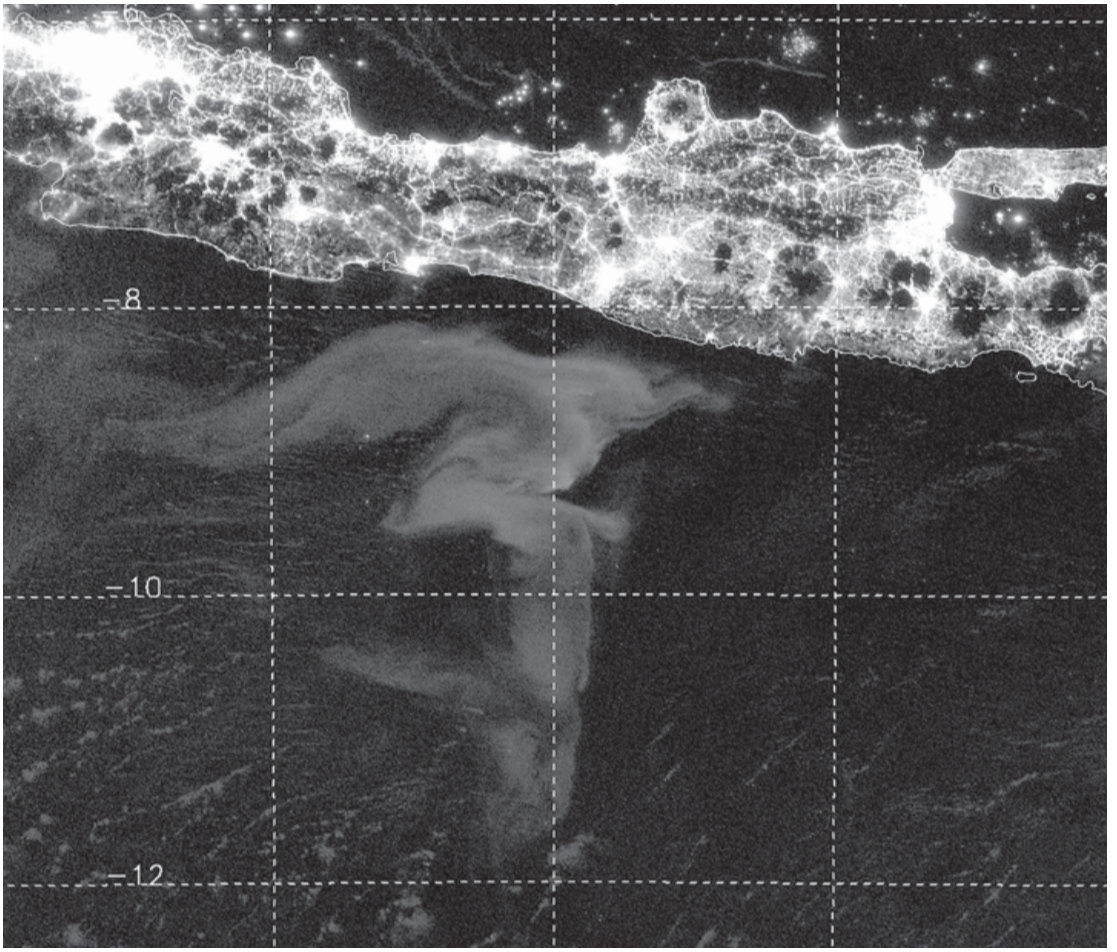

A MILKY SEA sprawling across almost 40,000 square miles of ocean south of Java in summer 2019 was captured by sensitive night-vision satellites; it lasted 45 days.

NOAA/Colorado State University/CIRA

trayed them as bad omens, describing a mariner's "silent, superstitious dread" on entering a "midnight sea of milky whiteness," as if "shoals of combed white bears were swimming round him." In Jules Verne's novel *Twenty Thousand Leagues Under the Sea,* written almost two decades later, the fictional marine biologist Pierre Aronnax is less perturbed by his voyage through a milky sea in the Bay of Bengal, calmly informing his assistant that "the whiteness which surprises you is caused only by the presence of myriads of infusoria, a sort of luminous little worm, gelatinous and without color."

Verne's character was on the right track, but it would be more than a century before science began to catch up with science fiction. In July 1985 a U.S. Navy research vessel encountered a milky sea off the Arabian Peninsula. The scientists onboard, who were conducting a broad study of marine bioluminescence, were equipped for this stroke of luck, and they quickly collected seawater samples for inspection. In addition to the dinoflagellates, copepods and other types of plankton associated with the familiar, flashing displays, the samples contained bioluminescent bacteria. The researchers suggested that milky seas occurred after algae colonies on the water's surface bloomed and died. When the dead algal cells ruptured, they released lipids subsequently consumed by bacteria, which then multiplied furiously, eventually becoming concentrated enough to produce a continuous glow.

Finally, milky seas had been established as a scientific phenomenon with a biological cause. But to understand where, when and exactly why they occurred, researchers needed more data than serendipity could provide.

SAILING OVER SNOW

FOR THE U.S. NAVY, marine bioluminescence is a practical concern because a patch of bright seawater can outline a submarine, turning it into an easy target. In the early 2000s Steven Miller, an atmospheric scientist then at the Naval Research Laboratory in Monterey, Calif., began to wonder whether satellite sensors could detect bioluminescence from above. The only sensors capable of observing visible light at night were those in the Operational Line Scan (OLS) system that flew on U.S. Air Force satellites. Miller knew that most surface displays of marine bioluminescence were much too small to register on the sensors, so, on a whim, he searched the Internet for mentions of widespread bioluminescence. He turned up a description of milky seas on the website Science Frontiers, an idiosyncratic catalog of "unusual & unexplained" happenings then maintained by physicist William R. Corliss.

Miller, his curiosity piqued, began to collect eyewitness accounts. Among them was a relatively recent report

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from a British merchant ship, the SS *Lima,* which had sailed through a milky sea along the Horn of Africa on January 25, 1995. "The bioluminescence appeared to cover the entire sea area, from horizon to horizon," read the *Lima*'s log entry, "and it appeared as though the ship was sailing over a field of snow or gliding over the clouds."

When Miller pulled up the OLS images from the *Lima*'s location on that date, he initially saw nothing. But when he zoomed in, he saw a faint, comma-shaped smear. "It looked like a finger smudge, but it moved as I moved the figure," he remembers. Miller found that the edges of the smudge matched the coordinates noted in the ship's log as it entered and exited the milky sea, which covered nearly 5,500 square miles. When he examined OLS images from the days immediately before and after the *Lima*'s encounter, he found the same smudge, rotating counterclockwise in concert with local ocean currents. "Okay," Miller thought, "we *can* see bioluminescence from space."

Miller got in touch with Steven Haddock, a marine biologist at the nearby Monterey Bay Aquarium Research Institute (MBARI), to share his findings. Like Miller, Haddock had never seen a milky sea firsthand, but he was familiar with the phenomenon, especially because one of his mentors, marine biologist Peter Herring (now retired), had cataloged hundreds of descriptions of milky seas dating back to Captain Semmes and the *Alabama*. Haddock, who primarily studies bioluminescence in jellyfish, had spent much of his career trying to get as close as possible to bioluminescent organisms using crewed or remotely operated deep-sea submersibles. He and Miller began to collaborate.

Although the OLS detection from 1995 had been something of a fluke—the product of Miller's persistence and a fortuitous satellite position—Miller hoped a new, more sensitive low-light visible-spectrum instrument called the day-night band (DNB) sensor would allow a systematic survey of milky seas. The sensor, launched in 2011, now rides on two satellites more than 500 miles above Earth's surface, each orbiting the planet daily. More than 100 times as sensitive as the OLS, the DNB can easily pick up the gleam of a milky sea. But it can also pick up the faint "airglow" produced by the absorption of ultraviolet light in the upper atmosphere, some of which is reflected by clouds. "There were clouds everywhere. The airglow is emitting upward, and sometimes it makes this really diffuse, widespread veil of light," Miller explains. Differentiating bioluminescence from these other phenomena, he adds, "took us many years of looking at what seemed like very noisy imagery."

Thanks to the long history of sightings by mariners, Miller and Haddock knew that the occurrences of milky seas peaked in winter and summer and that they were most often reported in the northwestern Indian Ocean, where both the *Alabama* and the *Lima* had encountered them, as well as around Indonesia, in particular near the island of Java and in the Banda Sea. Narrowing his search to these seasons and locations, Miller analyzed DNB data collected on moonless nights from 2012 through 2021, eventually identifying a dozen events that were not clouds or airglow, were invisible during the day and drifted with the currents over multiple nights. One 2019 event, detected just south of Java, was visible for at least 45 nights and covered almost 40,000 square miles—an area the size of Kentucky. Its multiweek persistence suggests that the DNB sensor could be used to dispatch researchers to newly formed milky seas in time to conduct dives in them. "[There's] only so much you can do from spaceborne measurement," Miller says. "You can't get into the water, you can't see the vertical structure of the glow within water, you can't sample the critters, you can't measure the detailed chemistry. [For] all these things, you need to be in the middle of it to truly understand."

While Miller waits for the chance to be in the middle of a milky sea, he continues to expand his collection of sightings. A recent addition comes from Sam Keck Scott, who in the summer of 2010 helped to sail a restored Dutch ketch from Malta to Singapore, crossing the Arabian Sea. One evening in late July, as Scott began his watch, he noticed an odd radiance in the air. After a few minutes he realized that even though the sky was completely dark he could see the boat's sails and hull; the entire ocean had brightened and seemed to be shining from within. Scott and his crewmates sailed through the milky sea for about four hours, exiting it even more suddenly than they had entered. "We knew it was bioluminescence of some kind, but it was on this wild, wild scale, unlike anything I'd ever seen before," Scott recalls.

BURGLAR ALARM

FROM A DISTANCE, scientists have proposed various hypotheses about how milky seas form. Investigators on the 1985 navy expedition theorized that the bioluminescent bacteria they collected had congregated around an algal bloom. Other sleuths have since suggested that the steady glow results from "quorum sensing," the ability of bacteria to communicate through chemical signaling. Once their density is high enough to produce a perceptible collective glow, they sustain a continual shine. But why? Some biologists think bioluminescence in other marine organisms helps them attract food or mates or functions as a kind of burglar alarm, flashing when they are under attack in hopes of attracting the predators of their predators. The glow of quorum sensing in bacteria may act as a different invitation: when a colony runs low on food in the open water, it may glow to encourage nearby fish to come and consume the bacteria, consequently sustaining the bacteria in their guts.

The decade of DNB data complicates the idea that milky seas occur most frequently in winter and late summer. The peaks in milky-sea formation do appear to be strongest in the northwestern Indian Ocean when winter and summer monsoons trigger phytoplankton blooms by bringing deep, cold, nutrient-rich water to the sea surface. Farther east, however, milky seas may be set up by the Indian Ocean Dipole, an El Niño–like pattern of sea-surface temperatures associated with cool, dry conditions and strong winds in the eastern Indian Ocean between

DEEP-SEA inhabitants produce an amazing array of bioluminescence to communicate, attract mates or prey, or confuse predators. Counterclockwise from top left: a green brittle star; a firefly squid whose underside glows to camouflage it against the water above when seen by enemies below; a viperfish; two hatchetfish; a dragonfish; and the belly of a pearlside. Dots along the belly are photophores—organs that produce light through chemical reactions or symbiotic bacteria.

Jerome Mallefet/Minden Pictures; David Shale/Minden Pictures; David Shale/Minden Pictures; Jerome Mallefet-FNRS/Minden Pictures; Jerome Mallefet-FNRS/Minden Pictures; Solvin Zankl/Minden Pictures (*clockwise from top left*)

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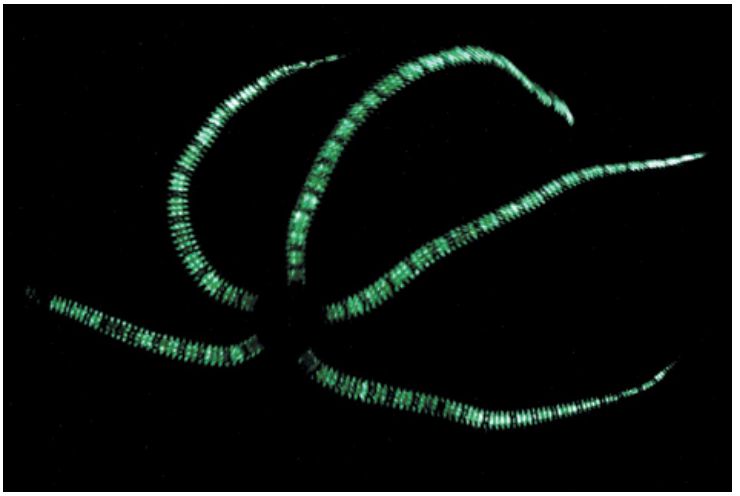

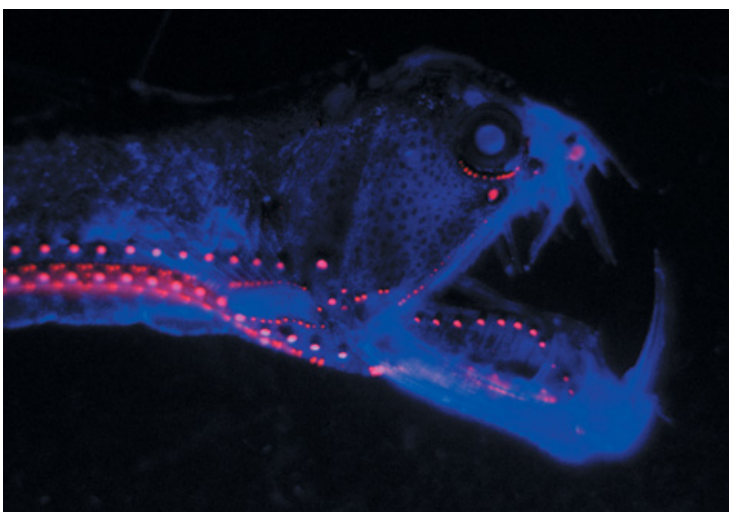

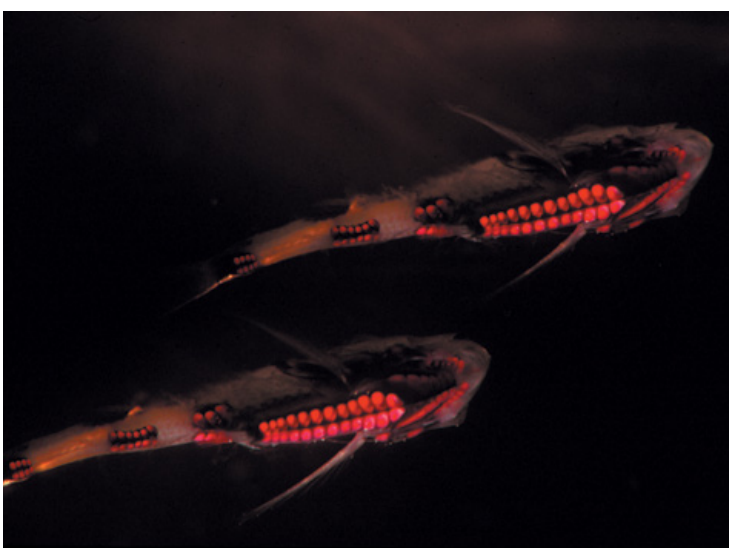

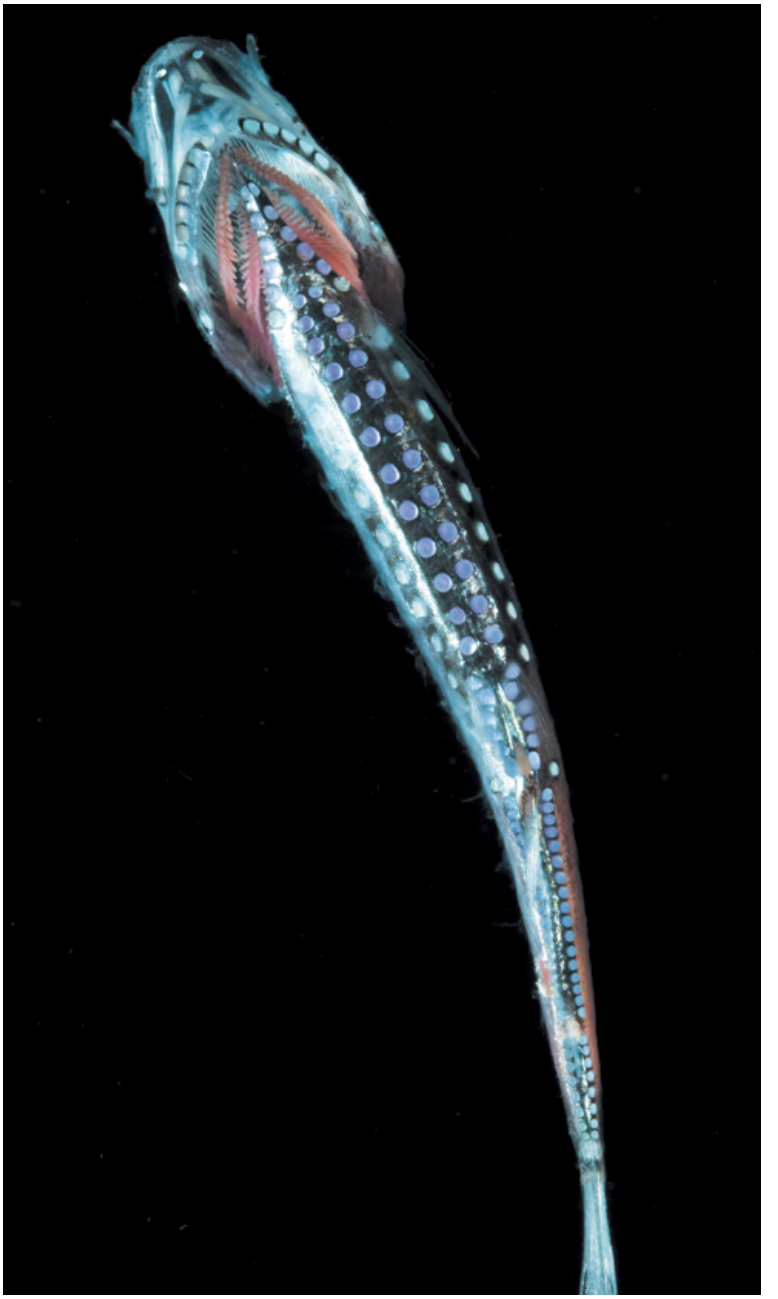

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May and October. The satellite data also suggest an explanation for why the glow occasionally seems to extend to some depth, creating the perception among mariners that their ship is suddenly floating in light: Miller found that several milky seas occurred in the relative calm between large ocean eddies, where a combination of currents and temperature gradients can isolate a column of seawater from the surrounding ocean, putting it at a standstill. Such conditions, he hypothesizes, could foster superdense bacterial populations whose quorum sensing extends vertically as well as horizontally to adjacent colonies, magnifying the depth and breadth of the resulting milky sea.

Miller and Haddock hope the DNB sensors' ability to detect—and, in time, perhaps predict—milky seas will allow researchers to quickly head out to the ocean and collect samples to test hypotheses. Until then, milky seas are unlikely to give up their lingering mysteries.

EVERYWHERE AGLOW

THE SECRETS of milky seas persist in part because much larger questions remain about the nature, function and extent of bioluminescence itself. Since most bioluminescent organisms live in the ocean, many at great depths, observing bioluminescence firsthand has required considerable resources—and not inconsiderable risk. Marine biologist Edith Widder, who founded the Ocean Research and Conservation Association in 2005, began her pioneering bioluminescence studies in the 1980s. She recounts her numerous and occasionally hair-raising submersible experiences—including a life-threatening leak at a depth of 350 feet—in her 2021 book, *Below the Edge of Darkness.* "I've spent a lot of my career in submersibles, operating in the dark" because only very recently have cameras been able to perceive both the light and the color of bioluminescence, she told me. "It's absolutely, breathtakingly beautiful, and finally [other people are] getting to see it."

Widder and other researchers who have managed to take deep-sea voyages have known for decades that bioluminescence is a common ability. But the first reliable estimate of its occurrence came in 2017, when Haddock and Séverine Martini, then a postdoctoral researcher at MBARI and now at the Mediterranean Institute of Oceanography, published an analysis of 17 years of video observations collected by remotely operated vehicles off the California coast. From more than 350,000 observations, which included more than 500 groups of organisms, taken at depths from just below the surface to nearly 13,000 feet, Martini and Haddock concluded that at least three quarters of the organisms were capable of bioluminescence. The percentage remained remarkably consistent at different ocean depths. In a 2019 study, they found that about a third of the organisms living on the ocean floor are bioluminescent. Martini identified a carnivorous sponge that was not only new to science but the first documented case of bioluminescence in its phylum.

Given that the ocean is the largest living space on the planet, the two analyses suggest that bioluminescence is one of the predominant ecological traits on Earth. "It's not something far away that you'll never see in your life," Martini says. "At sea, everything is glowing—you just have to pay attention." For Martini, Haddock, Widder and the few other marine bioluminescence researchers, the pervasive glow only increases their interest in its ecological functions, evolutionary history, chemistry and genetics—and their excitement about the high-definition underwater cameras and advanced genetic sequencing that offer new ways of exploring a once all but inaccessible world.

Humans have benefited greatly from bioluminescent species. Medical and biological researchers frequently use green fluorescent protein, which biologists isolated from bioluminescent jellyfish in the 1960s, as a visual marker of proteins and the components of living cells. Widder is using bioluminescent bacteria to identify pollution hotspots in Florida's Indian River Lagoon, one of the most diverse estuaries in North America. Fertilizer and pesticide runoff from farms and lawns, as well as leakage from sewage and septic systems, has been poisoning the lagoon for decades, and the pollution has accumulated in its sediments. Because most pollutants interfere with bacterial respiration and therefore with bacterial bioluminescence, Widder and her colleagues have taken sediments from the lagoon and mixed them with bioluminescent bacteria in the lab to determine the relative concentrations of pollutants throughout the lagoon—knowledge that helps in monitoring, mitigation and restoration efforts.

Although applications are expanding, the ability of marine organisms to benefit from their own bioluminescent capacity is under threat. The rush to mine valuable metals from the ocean floor is expected to tremendously impact not only the seabed but the entire deep sea, where the water is typically clear enough for bioluminescent organisms to communicate with one another across hundreds of feet. When robotic mining vehicles scrape the seafloor, they kick up clouds of sediment. After machines pump collected material to the surface and remove the fist-sized, metal-rich nodules, they dump the remaining mud and silt back into the sea, again clouding once transparent water—inevitably disrupting communication among the bioluminescent organisms and interfering with their ability to find food and mates.

"In the context of ocean ecology and ocean health, it's important to understand how widespread and widely used [bioluminescence] is," says Haddock, who co-authored a 2020 paper on the ecological effects of deep-sea mining. "If you do something that's going to affect that process, it's going to have all these ripple effects that we can only now start to appreciate." The glowing seas that so terrified generations of mariners have taken no victims and left no traces; the cloudy seas created by humans, however, could permanently dim the ocean's light. SA

Michelle Nijhuis is author of *Beloved Beasts: Fighting for Life in an Age of Extinction* (W. W. Norton, 2021), a history of the modern conservation movement. She lives in Washington State.

David Shale/Minden Pictures

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THE BLACK SEADEVIL, which lies in wait as deep as 13,000 feet, has a transparent lure rising from its head. Bacteria living inside the lure glow to attract prey. It is unclear how the fish controls the emissions.

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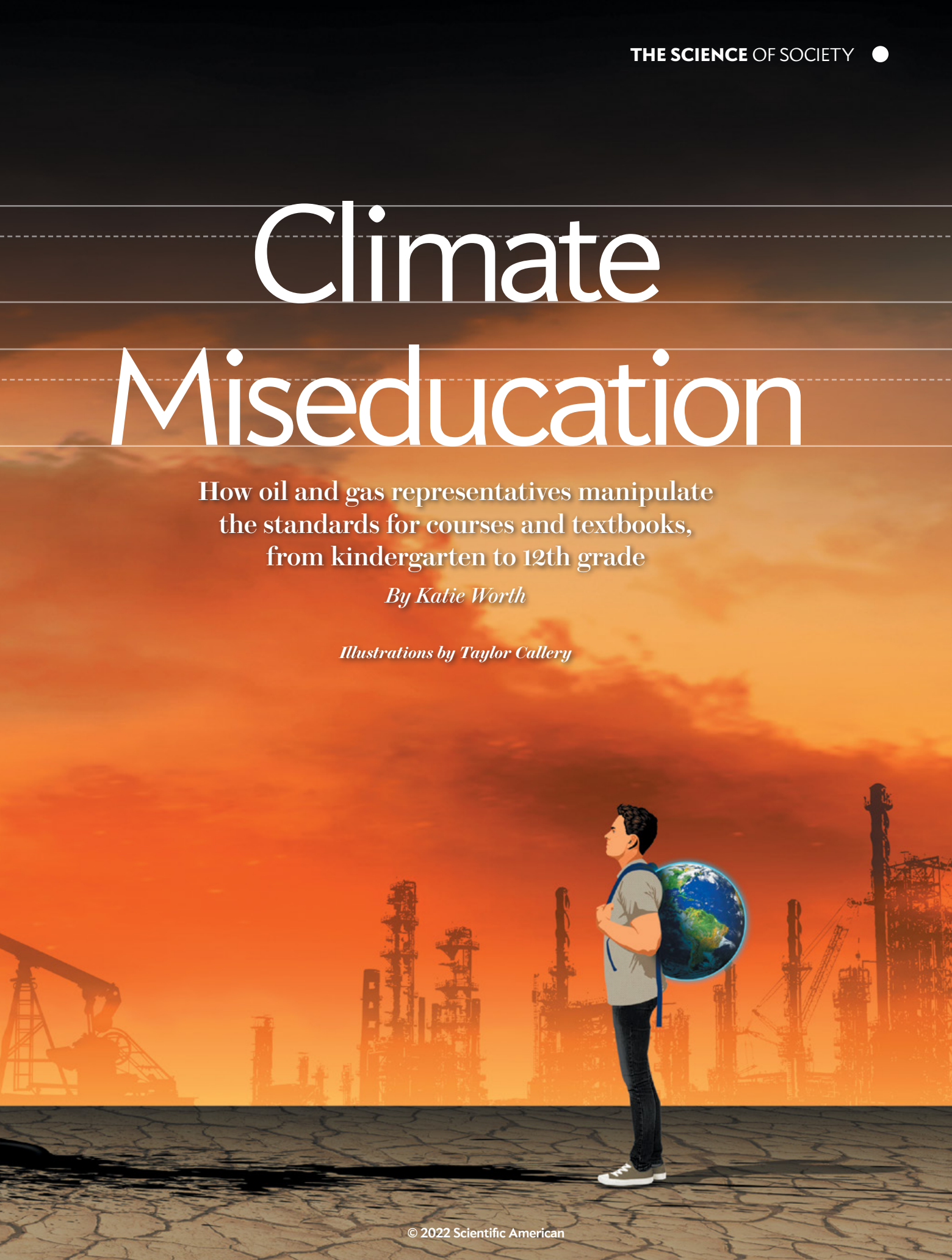
Climate Miseducation

How oil and gas representatives manipulate the standards for courses and textbooks, from kindergarten to 12th grade

By Katie Worth

Illustrations by Taylor Callery



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IN A DRAB HEARING ROOM IN AUSTIN, TEX., MEMBERS OF THE STATE BOARD OF Education, seated at small desks arranged in a broad, socially distanced circle, debated whether eighth grade science students should be required to "describe efforts to mitigate climate change." One board member, a longtime public school science teacher, argued in favor of the proposed new requirement. Another, an in-house attorney for Shell Oil Company, argued to kill it.

The attorney won. In the end, the board voted to require that eighth grade science students "describe the carbon cycle" instead.

Over the past few years school board meetings around the country have erupted into shout fests over face masks, reading lists and whether to ban education about structural racism in classrooms. In Texas, a quieter political agenda played out during the lightly attended process to set science education standards—guidelines for what students should learn in each subject and grade level. For the first time, the state board considered requiring that students learn something about human-caused climate change. That requirement came under tense dispute between industry representatives interested in encouraging positive goodwill about fossil fuels and education advocates who think students should learn the science underlying the climate crisis unfolding around them.

Standards adoptions are an exercise in bureaucracy, but the results wield great power over what is taught in classrooms. Publishers consult them as they write textbooks. State education officials use them as the basis of standardized tests. School districts call on them as they shape curricula. Teachers refer to them as they devise lesson plans. Every state adopts its own standards, but Texas adoptions have long had influence far beyond the state's borders.

In 2020 two major education advocacy groups—the National Center for Science Education and the Texas Freedom Network—hired experts to grade the science standards of all 50 states and Washington, D.C., based on how they covered the climate crisis. Thirty states and D.C. made As or Bs. Texas was one of six states that made an F. But because Texas is one of the largest textbook purchasers in the nation—and because its elected 15-member State Board of Education has a history of applying a conservative political lens to those textbooks—publishers pay close attention to Texas standards as they create materials they then sell to schools across America. As a former science textbook editor once told me, "I never heard anyone explicitly say, 'We can't talk about environmentalism because of Texas.' But we all kind of knew. Everybody kind of knows." In this way, the proceedings in an Austin boardroom influence what millions of children nationwide are taught.

Most Americans favor teaching kids about the climate crisis. A 2019 nationwide poll by NPR/Ipsos found that nearly four in five respondents—including two of three Republicans—thought schoolchildren should be taught about climate change. When the Texas Education Agency surveyed science educators across the state about what should be added to the standards, one in four wrote in asking for climate change or something adjacent, such as alternative energy. No one asked for more content on fossil fuels.

And yet, as I learned when I watched 40 hours of live and archived board hearings, reviewed scores of public records and interviewed 15 people involved in the standard-setting process, members of the fossil-fuel indus-

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try participated in each stage of the Texas science standards adoption process, working to influence what children learn in the industry's favor. Texas education officials convened teams of volunteers to rewrite the existing standards, and industry members volunteered for those writing teams and shaped the language around energy and climate. Industry members rallied to testify each time proposals to revise standards got a public hearing. When the board considered the rewritten standards for final approval, the industry appealed to members to advance their favored amendments, ensuring that the seemingly local drama in Austin will have outsized consequences.

For at least a decade the fossil-fuel industry has tried to green its public image. The Texas proceedings show that its actions do not always reflect that image. In little-watched venues, the industry continues to downplay the crisis it has wrought, impeding efforts to provide clear science about that crisis to a young generation whose world will be defined by it.

THE LAST TIME THE BOARD OVERHAULED THE TEXAS Essential Knowledge and Skills (TEKS) for Science, in 2009, it was chaired by Don McLeroy, a dentist from east-central Texas. McLeroy made his views on science education clear when he declared at one meeting, "Somebody's got to stand up to experts!" The board spent much of that adoption cycle clashing over evolution, but it also required that high school environmental science students debate something scientists hadn't debated for a long time: whether global warming is happening. McLeroy told a reporter he was pleased because "conservatives like me think the evidence is a bunch of hooey."

At the end of 2019, when it was time to begin another overhaul, McLeroy was gone. The board made it clear to the 85 volunteers recruited by the Texas Education Agency to draft the new standards that it hoped there would not be a fight over evolution again. It soon became clear the group would fight about climate science instead.

To start the process, board members carved the standards into three tranches that they would consider one at a time: first, high school core sciences, then high school elective sciences and finally grades K–8 sciences. The board would give each tranche to writing teams composed of volunteers. Professional content advisers, most nominated by board members, would provide feedback to the board on proposed changes.

Over the summer of 2020 one team took on the first tranche, the high school core subjects: biology, chemistry, physics, and an integrated chemistry and physics class. The core science standards were important for two reasons. The classes had sky-high enrollment; every year nearly half a million students took biology alone. And what happened with these classes would set the tone for the high school electives and for K–8. To the climate education advocates' dismay, when the Texas Education Agency posted the writing groups' results on its website in July 2020, the draft standards didn't contain a single reference to modern-day climate change. But there was still a chance to fix that omission. The state board would present the draft standards for public testimony, hearings and amendments.

The first major hearing took place in September 2020, held in person and virtually on Zoom because of the COVID pandemic. More than 30 teachers, parents and other education advocates showed up to testify that the climate crisis has biological, chemical and physical aspects that make it relevant to all the core classes. Three and a half hours into that meeting, however, someone with a different message appeared on the Zoom screen: Robert Unger, a silver-haired engineer from Dallas who had worked for the oil and gas industry for more than 45 years. He was representing the Texas Energy Council, and he had some suggestions.

After hours of testimony, Robert Unger appeared to represent the Texas Energy Council, and he had some suggestions.

The Texas Energy Council is a coalition of about 35 industry organizations, predominantly from the oil and gas sector, collectively made up of more than 5,000 members. Some months earlier the council had begun recruiting volunteers to participate in the standards adoption process. "The earth sciences and the oil/gas industry in particular have suffered significant degradation in the K–12 curriculum over time," a page on the council's website said. In hopes of reversing that trend, the council enlisted 17 people—geoscientists, petroleum engineers, professors, attorneys and other fossil-fuel careerists—who, the site said, "shared its vision of ensuring that oil/gas is portrayed in a balanced fashion as a critical contribution to the Texas, U.S. and worldwide energy mix." Unger had helped organize the volunteers. (Several members of the organization, including Unger, declined to be interviewed for this story. In an e-mail exchange, Michael Cooper, president of the council, took issue with some of this article's findings but said he would be unable to provide a comprehensive response without reviewing a complete draft.)

Unger asked the board to remove a line in the introductory material for each of the high school core classes that discussed social justice and ethics, terms he said "do not belong in the course material." Instead, he said, the standards should include the concept of cost-benefit analysis.

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Most board members had expressed little reaction to the many people testifying in favor of climate education, but Unger's testimony got their attention. Longtime Republican member Barbara Cargill, a former biology teacher from north of Houston serving her last few months on the board, asked Unger how cost-benefit analysis might be incorporated into the science TEKS. He gave an example: The main benefit of fossil fuels is the energy they produce, and the costs are "environmental issues that our industry is already regulating." But oil and gas aren't the only fuels with a cost, Unger said. Take solar: "It seems like the benefits are wonderful, but the costs, in fact, are the mining of rare minerals to create batteries," he said. "Wind equally has cost and benefit to it." A science teacher could weigh these things with students, he noted, "and not get into the ambiguities of social injustice and social ethics." Cargill promised to consider Unger's proposal.

All sources of energy come with costs. But a fixation on "cost-benefit analysis" is a plank in a raft of arguments supporting what climate scientist Michael Mann has called "inactivism"—a tactic that doesn't deny human-caused climate change but downplays it, deflects blame for it and seeks to delay action on it. Sure, this brand of thinking goes, fossil fuels have their ills. But what form of energy doesn't? Mann and others have criticized such arguments for their false equivalencies: the environmental and health costs of rare earth minerals for certain renewable energy sources are small compared with those of fossil fuels.

The next day, when the board met to consider amendments to the standards, Cargill delivered. She proposed removing social justice from the standards and adding cost-benefit analysis. Fellow Republican Pat Hardy, a retired history teacher and curriculum developer representing suburbs near Dallas–Fort Worth, eagerly supported the addition. "People talk about electric cars like they're saving the universe," Hardy said, captured on a video of the meeting. "And the answer is no, they are not." The board voted to accept the changes. It was the Texas Energy Council's first major victory.

The climate education advocates did get a win on the final day of the hearings. Marisa Pérez-Díaz, a Democratic board member from San Antonio and the youngest Latina to ever be elected to any state's education board, had heard their pleas. She proposed adding the words "and global climate change" to the end of a standard that asked students to examine a variety of human impacts on the environment. Remarkably, the board approved the motion. It wasn't a big win; the wording applied to just one standard, for the integrated physics and chemistry course, which is taken by a fifth of the students who take biology. But for the advocates it was a hopeful sign—certainly a step up from "a bunch of hooey."

In the following months, as the board considered the next two tranches—the high school electives and the K–8 standards—Texas Energy Council volunteers showed up at meeting after meeting. Sometimes they pursued changes that the climate education advocates found reasonable, such as requiring that students learn the laws of geology and encouraging the use of resources such as museums and mentors. But they kept a relentless focus on adding cost-benefit analysis to the standards, and they added new petitions. They insisted on removing the terms "renewable" and "nonrenewable" to describe different energy sources; they preferred to describe all the options as "natural resources." And they frequently brought up energy poverty—the lack of access to affordable electricity. "Energy poverty is one of the gravest but least talked-about dangers facing humanity," testified Jason Isaac, director of an energy initiative for a conservative think tank, at one meeting. He suggested just one solution: "Right here in Texas the key to ending global energy poverty lies under our feet."

The climate education advocates on the board expected to lose some of these battles. But they hoped the Texas Energy Council volunteers would stand down when it came to including clear information about the science of the climate crisis. During the next set of deliberations, it became evident that would not be the case.

In January 2021 the board held the first hearings for high school electives: environmental science, aquatic science, earth science and astronomy. Far fewer students take the electives than take biology, chemistry or physics, but the earth science and environmental science course standards were the only ones that already mentioned climate change.

In the months leading up to the hearings, the 23 people on the electives writing teams had met about every two weeks to draft the new standards. The old standards for the earth science course had asked students to "analyze the empirical relationship between the emissions of carbon dioxide, atmospheric carbon dioxide levels, and the average global temperature trends over the past 150 years," a reference to the period since industrialization, during which atmospheric carbon dioxide levels have soared. That language didn't sit well with William J. Moulton, a longtime geophysicist for the petroleum industry. Encouraged by the Texas Energy Council, he and several other industry representatives had applied to the Texas Education Agency for a seat on a writing group and had been placed. Moulton was on the team rewriting the earth science and astronomy courses.

Moulton agreed that climate change should be mentioned in some way because students would hear about it anyway. But he felt students should not be led to believe the science is settled. He argued that the phrase "the past 150 years" should be removed. The group agreed to that change and to several of Moulton's other language tweaks. When those already diluted standards came before the board in January, four other Texas Energy Council volunteers appeared on Zoom, all recommending amendments. One person said the standards should focus on the dangers of rare earth minerals. Another said it was important for chil-

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dren to learn that the inception of the fossil-fuel industry stopped the practice of whaling for blubber that could be turned into fuel. "Oil and gas literally saved the whales," she said.

The industry also had a new champion on the board: Will Hickman, who had just been elected in November 2020 for a district outside of Houston. Hickman's experience in education included serving on parent groups at his kids' schools, coaching community sports and teaching Sunday school. He'd held the same day job since 2004: senior legal counsel at Shell Oil.

In the January hearing, Hickman's first, his opening question was where in the proposed standards he could find the advantages and disadvantages of various forms of energy. The next day he offered an example that might be raised in class: "Everyone thinks renewable power's a great idea, and Germany adopted it on a large scale," he said. "But the cost-benefit—it ended up raising their power prices to about 2.5 times our power prices."

The writing committees had already included a reference to cost-benefit analysis in the "scientific and engineering practices" section of each of the elective courses, and the standard for the environmental science course had a second mention. But at the next board hearings, in April, Hickman pressed for more. Another member, Rebecca Bell-Metereau, a professor of English and film at Texas State University, who had just been elected to represent Austin, pressed back: "The very phrase 'costs and benefits' places the primary emphasis on money, not on society or well-being or human health." The board nonetheless approved a motion by Hickman to add another mention of costs and benefits, to aquatic sciences.

Moulton began showing up at the board hearings with additional proposed changes. His colleagues on the writing group had accepted some of his suggestions but not all of them, so he wanted the board to consider adding them as amendments. In the final hearing in June 2021, board member Hardy asked Moulton if he'd heard the "newest stuff that's been coming out on climate," which, she said, was that the climate crisis was not unfolding as scientists had predicted. Moulton suggested that the consensus about warming had been exaggerated by scientists in pursuit of grant money.

Hardy began proposing amendments word for word from Moulton's suggestions. This elicited an outcry from Bell-Metereau. "Do you not think that if someone's area of work is in fossil fuels that they might have some bias on this issue?" she asked Hardy. "It might be that *I* have a bias for the fossil-fuel industry," Hardy answered.

Bell-Metereau and others on the board threatened to delay the entire adoption if Hardy insisted on moving the changes forward. Ultimately Hardy dropped the proposals. But Moulton and the council had already succeeded in important ways: The new electives standards had multiple references to cost-benefit analysis. The terms "renewable energy" and "nonrenewable energy" were removed in several places. The single mention of the effects of burning fossil fuels in the old standards was gone, and the strongest description of climate change had been weakened.

THE CLIMATE EDUCATION ADVOCATES had failed to install a robust presentation of the science surrounding the climate crisis in any of the high school core or elective classes, as they had watched the Texas Energy Council volunteers achieve one goal after another. But they held out hope for the K–8 standards. Nearly every middle schooler takes the same sciences, and the classes cover weather and climate systems, an obvious and effective place to discuss the crisis for a generation of students that would have to live with its consequences.

> "Inactivism" doesn't deny human-caused climate change but downplays it, deflects blame for it and seeks to delay action on it.

On a 96-degree day at the end of August 2021, the board held a public hearing on the K–8 standards, in person and virtually. The writing groups had labored over the drafts, adding a single passage mentioning climate change. Eighth grade science students, the draft declared, would be expected to "use scientific evidence to describe how human activities can influence climate, such as the release of greenhouse gases." One writing group, which included the executive director of a natural gas foundation, had also appended a note stating it had not been able to reach consensus on a proposal to add another line: "Research and describe the costs and benefits of reducing greenhouse gas emissions versus global energy poverty."

At the hearing, two of the professional content advisers who had reviewed the standards gave the board radically different opinions. Ron Wetherington, a retired anthropology professor from Southern Methodist University nominated by Pérez-Díaz, argued that the climate standards needed significant strengthening. Among other things, he advocated that the word "can" be dropped from the phrase "describe how human activities can influence climate." "Can" implies that something is a possibility, but an abundance of evidence shows that the influence is already taking place. He also asked the board to add an expectation that students explore efforts to mitigate the crisis. Because students would learn that it's happening, he posited, they should learn what people are doing to fix it.

Gloria Chatelain, a longtime educator and CEO of her own consulting firm called Simple Science Solutions, who had been nominated by Hardy and Cargill,

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stood in total opposition. She began her testimony by praising the "absolutely amazing job" the Texas Energy Council had already done in improving the standards. She also said human-caused climate change should be treated very lightly in middle school, if at all. "Our goal is not to produce angry children but children who love science. We're challenging them to go solve some of these exciting problems but not turn them into Gretas," she said, referring to the teenage climate activist Greta Thunberg of Sweden. Instead, she contended, the board should add an expectation that students "research and describe the role of energy in improving the quality of life in reducing malnutrition and global poverty," language the council had suggested. "I think it needs to go in, guys. It's very, very important that we address it," Chatelain said.

For three days that week the board considered the K–8 language. Over the protests of Democrats, Hardy moved to add "cost-effectiveness" to each middle school class. She and Hickman persuaded the conservative board majority to change multiple references to renewable and nonrenewable energy to "natural resources" in the elementary standards.

On the second day climate education advocates landed two unexpected victories. Pérez-Díaz proposed rewording the climate standard to "describe how human activities over the past 150 years, including the release of greenhouse gases, influence climate." Then she proposed adding a separate line: "Describe efforts to mitigate climate change, including a reduction in greenhouse gas emissions." The amendments both carried. But on the third day the board axed the reference to the past 150 years and added the word "can" back in. The details of recent climate change, Hardy argued, would simply be too hard for eighth graders to grasp.

Aicha Davis, a board member from Dallas who spent 11 years teaching science before pursuing her Ph.D. in education leadership and policy, spoke up. "With all respect to my colleague, you've never taught eighth grade science," she said, her voice tinged with forbearance. "We absolutely can't let the oil and gas industry dictate what our kids need to learn when it comes to science. It shouldn't be about the Texas Energy Council. It should be about what's best for our students." Neither scientists nor educators had voiced concern about teaching

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climate change to eighth graders, she noted. "So let's call this what it is. At this point we're only making votes based on what oil and gas wants us to do."

Hickman, the Shell attorney, turned on his microphone. "A few thoughts and reactions," he said. "One is I think our permanent school fund is generally funded by oil and gas," referring to a major source of education funding maintained in part by proceeds from fossil fuels reaped from public lands. "All of us are probably going to get home using oil and gas.... If all of this is true—greenhouse gases are evil—what do we do? Do we ban gasoline and stop using gasoline-powered cars? Do we ban diesel for trucks? How do we get our Amazon and Walmart purchases?" The board chair suggested they table the issue until the final round of hearings, scheduled for November 2021.

As they waited for the last round, the National Center for Science Education and the Texas Freedom Network organized. They recruited 67 Texan climate scientists to join a letter asking, among other things, that the word "can" be dropped from the climate passage and that the mitigation language stay put not only because it consisted of "basic knowledge" that every citizen should have but because it would provide students with a sense of hope.

Nevertheless, the final round of deliberations in November was a slaughter. Climate change had been added in a limited way to the standards, and the conservative majority supported that. But it rejected a motion to strike the word "can." It blocked a motion to remove cost-benefit analysis from the middle school sciences. It approved new language about "the critical role of energy resources" in modern life. It inserted a reference to rare earth elements. It introduced the concept of global energy poverty.

Last, Hickman moved to drop the climate mitigation standard that Pérez-Díaz had managed to add in September, arguing that the subject was more appropriate for social studies than for science and that it "just seems above and beyond for an eighth grade student and teacher." The board Democrats fought the change, but they were outnumbered. The board replaced the mitigation standard with the line "Describe the carbon cycle."

The Texas Energy Council and two allied organizations issued a press release praising the State Board of Education for adopting standards that "emphasize the critical role of energy in modern life." The Texas Freedom Network hit a more ambivalent note in its year-end report. "The State Board of Education could have—and should have—done much better. But our campaign resulted in new science standards that for the first time make clear to Texas public school students that climate change is real and that human activity is the cause."

The fossil-fuel industry, like some others, has worked for decades to get its messages in front of schoolchildren. I have found examples across the U.S. Petroleum companies regularly fund teacher trainings incentivized by free classroom supplies. Industry organizations have spent millions of dollars producing and distributing energy lesson plans. I witnessed an oil and gas industry employee giving a PowerPoint presentation radically downplaying the climate crisis to a class of seventh graders.

Even with abundant online educational materials, just 9 percent of high school science teachers say they never use a textbook. The nation's most popular middle school science textbooks are replete with language that conveys doubt about climate change, subtly or otherwise. In one textbook that, as of 2018, was in a quarter of the nation's middle schools, students read that "some scientists propose that global warming is due to natural climate cycles." In fact, the number of climate scientists who support that idea is effectively zero.

"Let's call this what it is," Aicha Davis said. "At this point we're only making votes based on what oil and gas wants us to do."

Texas isn't the only major buyer of textbooks. Other large states such as California have adopted standards that embrace the science of climate change, leading to a divide. Textbook publishers create one set of products to sell in Texas and states that lean the same way and a second set of products for states aligned with California. This poses an equity problem: the education a child receives on an issue central to the modern world depends on what state they happen to live in.

In April 2022 the Texas Education Agency issued a call for textbooks based on the new standards. Publishers were given a year to submit materials to the agency. Review panels, made up of educators, will search the textbooks for errors and rate how closely they follow the standards. Then the materials go before the state board for approval or rejection. Texas school districts have the option of establishing their own textbook adoption process but still must choose books that comply with the standards. Most just defer to the board's choices. The new science textbooks should be on classroom shelves starting in the fall of 2024.

The Texas Energy Council's Moulton told me he found the standards adoption process energizing, and he hopes to stay involved. As soon as he gets the chance, he said, he'll start reviewing the new textbooks and will head back to the board to give them his thoughts. SA

Katie Worth is a freelance writer in Boston. She is author of *Miseducation: How Climate Change Is Taught in America* (Columbia Global Reports, 2021).

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The Power of Viking Women

Analyses of ancient North Atlantic textiles show that Viking and medieval women wielded considerable cultural and economic influence

By Francine Russo

Illustration by Chase Stone

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ARCHAEOLOGY HAS A REPRESENTATION PROBLEM. FOR most of the time that scholars have been probing the human past, they have focused mainly on the activities of men to the exclusion of women. There are a couple of reasons for this bias. One is that the kinds of artifacts that tend to be preserved well are made of inorganic materials such as stone or metal, and many are associated with behaviors stereotypically linked to men, such as hunting. Another reason is that early archaeologists were mostly men and more interested in men's work than in women's. As a result, our understanding of past cultures is woefully incomplete.

In recent years archaeologists have sought to fill that gap in our knowledge, in part by taking a closer look at traditionally ignored remains such as textiles, which had long been dismissed as trivial. Cloth rarely survives the centuries because it decomposes easily except under ideal preservation conditions. But even in a fragmentary state, it contains a wealth of information about the people who made and used it.

Michèle Hayeur Smith, an anthropological archaeologist at Brown University, has been at the forefront of efforts to glean insights from ancient cloth, scouring archaeological sites and museum collections for textiles that could illuminate the lives of women in early North Atlantic societies. Her work has shown that the Vikings never would have expanded their known world without the women's work of weaving.

Hayeur Smith's study of early North Atlantic textiles took off from the basement storage area of the National Museum of Iceland, its rows of metal shelving bursting with boxes and bags of dirt-covered cloth. She first visited in 2009 to inspect the museum's collection of remains from the Viking Age and later periods. "It was literally thousands of fragments," she says. Yet they were just sitting there, hardly examined by anyone.

Hayeur Smith grew up surrounded by fabrics her anthropologist mother collected from around the world. In her 20s Hayeur Smith earned a fashion degree in Paris. She knew that the way people in the past clothed themselves and wove everything from currency to cloaks could reveal a great deal about a lost culture, especially its women. In the 1990s, as a Ph.D. student at the University of Glasgow, she'd devoted herself to studying Viking women's dress and ornament, typically from artifacts found in burial sites. Inspired by her first glimpse of the wealth of textile remnants in the museum's storeroom, Hayeur Smith eventually decided to uncover the lives of the ordinary women who stood weaving at their looms.

Ever since then, she has been analyzing textiles spanning 900 years of history, starting with the Viking settlement of Iceland in C.E. 874. She has pored over thousands of soil-encrusted fragments dense with information about the women who made the fabric. Her resulting studies of that museum's neglected collection of little brown scraps, as well as many other specimens of ancient Viking and later North Atlantic fabric, are among the first to prove the old guard wrong about the importance of cloth and women in ancient societies.

Textiles *trivial?* In my Zoom interview with her, Hayeur Smith, blond hair spilling to her waist, calling

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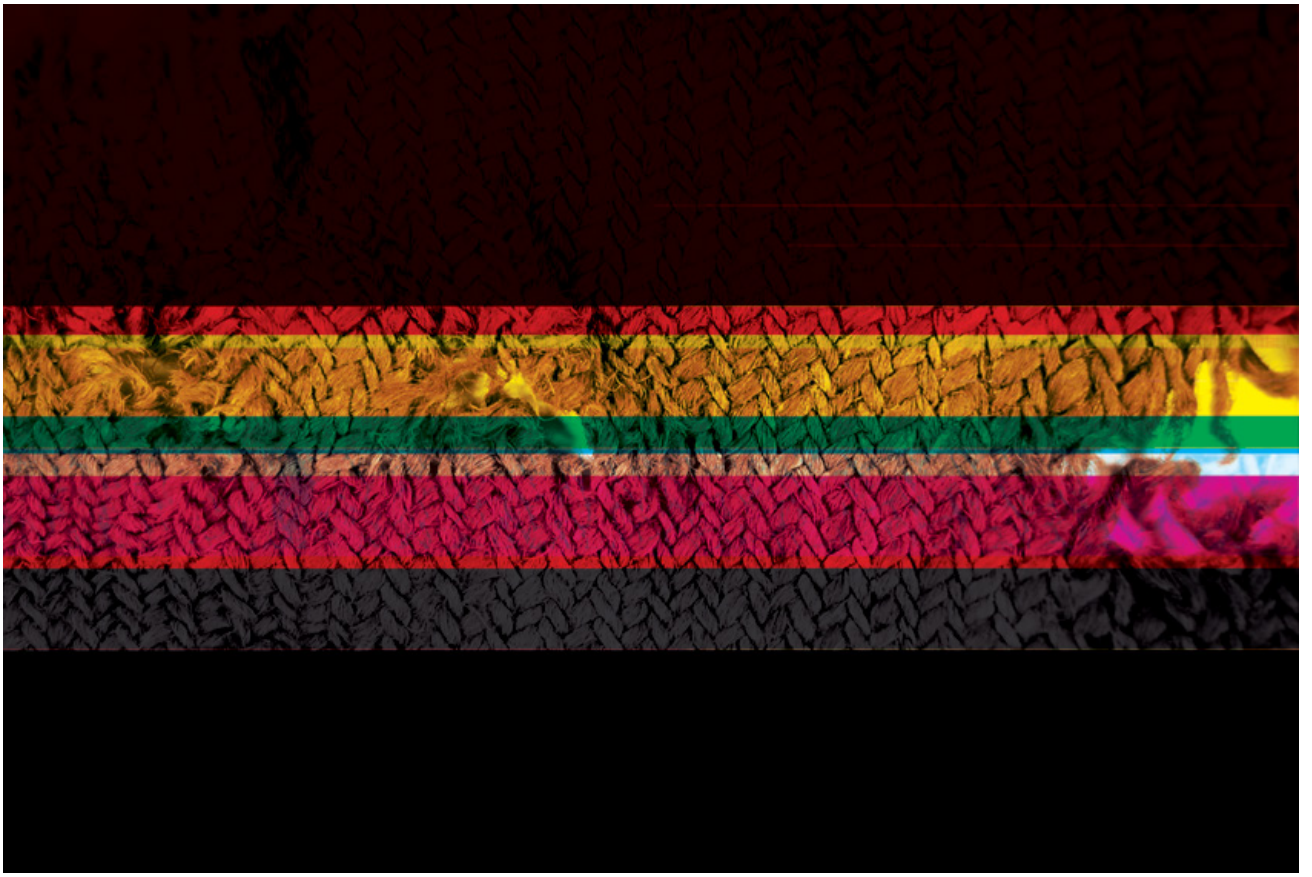

LEGAL CLOTH known as *vaðmál* was recovered from late 17th–century archaeological deposits at the site of Gilsbakki in western Iceland. Gilsbakki was the seat of Viking Age and medieval chieftains from around C.E. 900 to C.E. 1210.

to mind a Valkyrie, speaks in a voice ringing with conviction: "No. Textiles and what women made were as critical as hunting, building houses and power struggles," she says. In the Viking and medieval eras, women were the basis of the North Atlantic economy, and their cloth allowed people to survive the climate of the North Atlantic.

HIDDEN FIGURES

IN POPULAR CULTURE, Viking women are seen through the eyes of the era. In the 1950s they were portrayed as weak and subservient to men. In the 1970s they were sexualized. In recent shows such as *Vikings* and *The Last Kingdom,* they are depicted as shield-maidens or warriors.

Until Hayeur Smith began her work, the real lives of Viking women were largely unknown to science. According to archaeologist Douglas Bolender of the University of Massachusetts Boston, who studies the Viking Age and the medieval North Atlantic, the basic outline of Viking society came from the Icelandic sagas. Those book-length narrative accounts were set down more than 300 years after the events they describe. And the authors, who were men as far as we know, were Christianized people writing about their "pagan" ancestors.

Viking women have long been stereotyped in archaeology as performing primarily domestic tasks: child-rearing, cooking, weaving and making clothing. Written accounts and archaeological evidence confirm that they were weavers. Yet for years at a time during their husbands' absences for raids or trading expeditions, women ran the farms and engaged in trade, Hayeur Smith says.

"There's some truth" to the idea that we've found women's work less interesting, says archaeologist Thomas McGovern of the City University of New York. McGovern, whose full white beard evokes an Old Testament patriarch, entered archaeology in the 1970s. "Mostly it was old white guys," he recalls. Since then, however, the field has changed for the better, he says, with far more women and diversity generally.

Yet traditional views of women still color researchers' interpretations of evidence, says archaeologist Marianne Moen of the Museum of Cultural History in Oslo. A Viking expert who studies gender in the archaeological record, she says that she regularly sees how the meaning of artifacts is distorted by preconceptions of what they must signify. For example, a grave filled with a warrior's weapons at the Viking site of Birka in Sweden was long thought to be a man's final resting place until DNA evidence proved it was a woman's.

Alexandra Sanmark of the University of the Highlands and Islands in Perth, Scotland, an authority on Vikings and medieval archaeology, agrees. A man bur-

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ied with scales is seen as a merchant, she says, but a woman buried with scales must be a merchant's wife, despite ample evidence that women conducted trade.

WRITTEN IN CLOTH

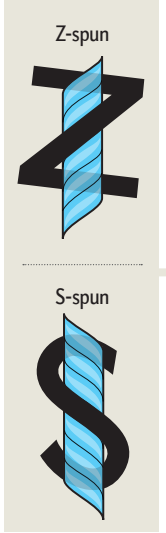
HAYEUR SMITH DECIDED to seek out North Atlantic women in the work of their hands. So little has been known about them until now, she says, "because it was men analyzing this from the perspective of men and medieval law codes written by men. Nobody had gone and looked at the actual stuff made by women."

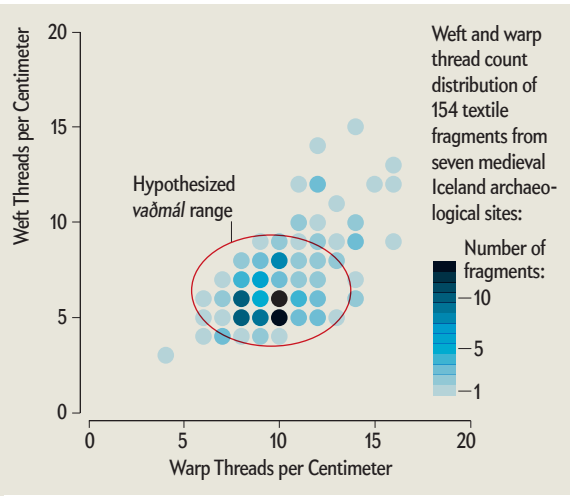
She did not begin her textile analysis completely from scratch. There had been a few studies of textiles, most notably by the late Elsa Guðjónsson, whose work was foundational for Hayeur Smith. Guðjónsson, however, had been able to study only "a handful" of archaeological pieces of fabric from the mountain of artifacts in the Iceland museum's collection, Hayeur Smith says. And Guðjónsson's work, like that of other textile analysts, focused mainly on technical details such as thread counts, weave types, fleece varieties, embroidery stitches and tools used to make them to understand the techniques of weaving.

For Hayeur Smith, the technical details were important, but she had a different goal: to create what she calls a "social archaeology" of the culture through which she could uncover the lives of the women who created the cloth. For this purpose, she focused on the everyday "homespun"—plain woolen fabric—made by ordinary women, who left no elaborate graves on their farms throughout the North Atlantic. Their only memorials are the textiles they wove on their warp-weighted looms.

Hayeur Smith demonstrated the Vikings' style of weaving at an event organized by the Haffenreffer Museum of Anthropology at Brown in 2020, a recording of which is available on YouTube. A wood horizontal bar resting on two vertical ones holds the separate vertical warp threads, which are weighed down taut by volcanic stones of the kind that dot the shores of Iceland. Holding a heddle rod to separate the warp threads, she draws the continuous horizontal weft thread in and out of one or more warp threads. By varying the number of warp threads, weavers could create common Icelandic patterns, mostly basic weaves known as twills and tabbies.

Before about C.E. 1000, the loom would have been set up in a *dyngja,* a weaving hut, says University at Albany archaeologist Kevin Smith, Hayeur Smith's husband, who has excavated similar structures in Iceland. These pit houses, he explains, are dug down 1.5 to three feet deep, sometimes with turf walls above the pit and sometimes with wood walls that would have provided a space high enough for people to stand and work. With a stone-framed hearth in one corner to offer warmth and light, these small buildings—no more than nine by 15 feet in size—would have provided an intimate space fitting a loom and perhaps three women, spinning, weaving and sharing stories.





Source: *The Valkyries' Loom: The Archaeology of Cloth Production and Female Power in the North Atlantic,* by Michele Hayeur Smith. University Press of Florida, 2020 (*chart reference*)

Hayeur Smith made several trips to the museum's basement laboratory in 2010, examining specimen after specimen under a microscope, counting warp and weft threads, taking note of such characteristics as the spin direction of yarn, the kind of fiber used and the weave type. As she worked, Hayeur Smith entered her data and extracted small samples for further analysis and testing, including a type of radiocarbon dating called accelerator mass spectrometry.

For the next several years she studied fabric remains from museum repositories in Iceland, Greenland, the Faroes, Scotland and Norway. Wielding her digital caliper, she measured the diameter of the cloth fibers and the sizes of the remnants. For each specimen, she meticulously recorded the age, site of origin and manufacturing details such as warp threads per square centimeter.

Somewhere between the first and second year of this endless and "filthy" job, soil all over her fingers, Hayeur Smith had her eureka moment. "Look," she shows me on a video call, holding her book open to a graph and pointing to a thick cluster of circled icons. "The more sites I checked, the more I saw this pattern. Viking Age textiles were colorful and varied, but in medieval times, there is a complete shift into standardized cloth."

Regular modern cloth, Hayeur Smith explains, could vary from 75 to 300 warp threads, but in Iceland and only in Iceland, from the 12th through 17th centuries, every textile from every site fell into a tight range of four to 15 warp threads. In addition, the spin direction of the yarn—clockwise (Z-spun) versus counterclockwise (S-spun)—shifted almost completely from Z-spun warp and weft to S-spun in the weft in the 11th century. All these details are specifications for legal cloth, called *vaðmál.* "Women were making the money!" she says.

CLOTH CURRENCY

ICELAND'S BUDDING ECONOMIC SYSTEM was based on Norway's. Certain commodities—cloth, cows, but-

Graphics by Jen Christiansen

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ter, grain—were legally assigned a value based on their equivalent value in silver. Toward the end of the Viking Age, however, homespun woolen cloth became much more important as a form of exchange in Iceland than in Norway. Scholars believe this shift may have resulted from such factors as a scarcity of silver after the Vikings stopped raiding, population growth, and the colony's burgeoning wool production. "Although its value was still measured, in theory, against silver, this cloth … came to be legally regulated as an exchange good in and of itself," Hayeur Smith notes in her 2020 book *The Valkyries' Loom: The Archaeology of Cloth Production and Female Power in the North Atlantic*. The name *vaðmál,* she explains, is a combination of the Old Norse words *vað* ("stuff" or "cloth") and *mál* ("measure"), meaning "cloth measured to a standard." It is frequently mentioned as a measure and medium of exchange in Icelandic legal texts, as well as sales accounts, church inventories and farm registers, from the 1100s into the 17th century.

Women made all of the *vaðmál*. In fact, they were churning out huge quantities of it as both a unit of currency and a commodity to be sold near and far. *Vaðmál* could be used to pay taxes and tithes, but it could also be traded or sold for making clothes and other necessities. It was especially in demand in England, which produced its own luxury fabrics but needed great quantities of Iceland's cheap durable homespun to clothe peasants, the urban poor and common soldiers.

It's a modern idea that work done at home is "domestic" and lesser because it doesn't produce money, Moen says. In the North Atlantic world, "home was where work was done." In fact, as Hayeur Smith points out, *vaðmál* was a major income-generating product.

Scholars knew about *vaðmál* in an "abstract" sort of way, Hayeur Smith says, because it was precisely defined in the medieval law books. But the legal texts never mention the women weaving it, she points out. And nobody checked the cloth remains to see whether they conformed to the specifications in the legal texts.

In tandem with her textile analysis, she examined the legal texts—most of which had, thankfully, already been translated from Old Norse into modern English. Through painstaking inspection, she confirmed that the cloth Icelandic women wove conformed exactly to these standards: a 2/2 twill (a tweed), Z/S-spun, woven with four to 15 warp threads per centimeter. The cloth was also supposed to measure two "ells" in width and six ells in length (a little more than one yard wide and three yards long in modern measurements). Based on the fragments she analyzed, the Icelandic cloth "can be assumed to be about this size or bigger." That unit of cloth was equal to a certain weight of silver. "Everyone assumed the economy was a male thing," Hayeur Smith says. In fact, it was not the men but the women making the decisions.

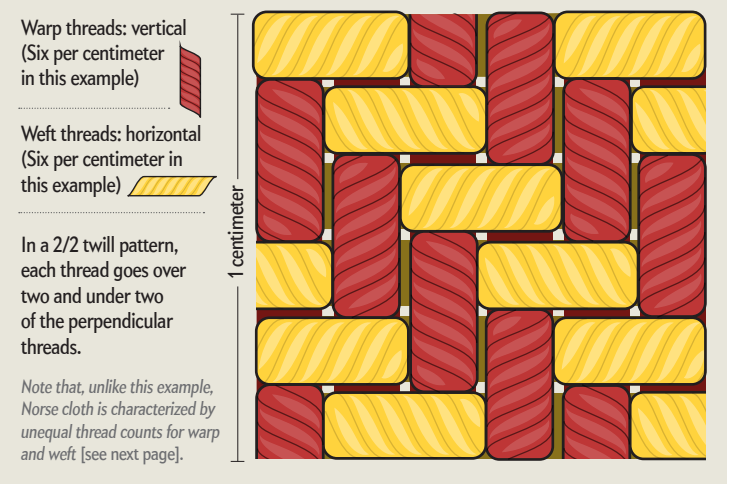
She suggests that women either created the specifications themselves or collaborated with men to do it. "It's hard to know what they were thinking," Hayeur Smith admits. "What's clear in looking at the time involved and the tools is that every able-bodied female in a household would have been involved." Indeed, at a certain level, "they may have controlled a lot of the narrative on these legal guidelines," she says. "It's not the men sitting there writing books … because [men] didn't go near weaving," she says.

LOOMING TABOOS

HAYEUR SMITH GROUNDS THIS assertion partly on evidence from poetic and mythological sources, including the Icelandic sagas, which provide clues to deep-seated attitudes toward women and weaving in the Viking Age and beyond. The power of women is expressed in the *Darraðarljóð* from Njáls saga, says Karen Bek-Pedersen, an expert on female aspects of Viking religion at Aarhus University in Denmark. In the saga, a soldier at the dawn of a battle has a vision in which he peeks into a *dyngja* and sees 12 Valkyries, Odin's female warrior spirits. They set up a loom and start weaving, using men's viscera as parts and threads. As they weave, they describe—and determine—the bloody defeat to come, Bek-Pedersen explains. She quotes this stanza:

The fabric is warped
with men's intestines
and firmly weighted
with men's heads;
bloodstained spears serve
as heddle rods,
the shed is ironclad,
and pegged with arrows.
With our swords we must strike
this fabric of victory

Poems from the sagas probably predate the sagas themselves, Bek-Pedersen says. Filled with metaphor,


Warp threads: vertical (Six per centimeter in this example)
Weft threads: horizontal (Six per centimeter in this example)
In a 2/2 twill pattern, each thread goes over two and under two of the perpendicular threads.
Note that, unlike this example, Norse cloth is characterized by unequal thread counts for warp and weft [see next page].
1 centimeter

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alliteration, rhythm and rhyme, they are hard to alter and easy to remember, making them likely to have been passed down through oral tradition.

The *dyngja,* Bek-Pedersen observes, can be seen as a space "charged with a feminine energy that reaches beyond the abilities of ordinary human women." In the literary canon, she says, men who hang out there and gossip with the women are portrayed as cowards or villains and invariably come to a bad end.

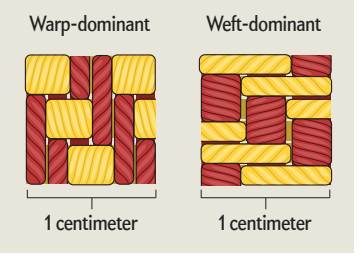
The fact that the *dyngja* was a space men shunned weighs heavily in Hayeur Smith's appraisal of women's power in cloth-making. Men feared that if they entered, they would lose their masculinity or even their lives. After Scandinavia turned Christian around C.E. 1000, looms were brought into the main living area of the *skáli,* the longhouse. Weaving would have been carried out in a separate area or room, with the taboos about this women's craft most likely undiluted. These taboos became a critical factor in women's power as their cloth turned into a major driver of the Icelandic economy.

CLOTH AND CLIMATE

IN 2011 HAYEUR SMITH met McGovern in a Chinese restaurant on the Upper East Side of Manhattan for what must have looked to an outside observer like a peculiar hand-off. McGovern had brought some fragile remains from an excavation he and his team had carried out a couple of years earlier at a site called Tatsipataa in southwestern Greenland. The workers had scooped up the textile bits separately from the bones he was studying, and he was happy to give them away, wondering what she could possibly learn from them. When he handed them over, he recalls thinking, "Well, good luck with this!"

Hayeur Smith was on a quest to find out why the cloth made by Greenland's women diverged so much from the cloth made by Iceland's female weavers. Greenland had been settled in C.E. 986 entirely by Icelanders. They were followers of Erik the Red, who'd been exiled from Iceland for manslaughter. The Greenlanders' cloth started out identical to the Icelanders' warp-dominant fabric but eventually shifted to contain more threads in its weft than its warp.

In the early 2000s the late Else Østergård, a textile expert at the Danish National Museum, proposed an explanation for the shift. Holding up her lovingly tattered copy of Østergård's 2004 volume *Woven into the Earth,* Hayeur Smith says Else thought it possible that Greenlandic women's weaving innovations might be a response to climate change during a period of cold climate known as the Little Ice Age. In Greenland, the first dramatic drop in temperatures started around roughly 1340 and continued with fluctuations through the mid-15th century, when its colonies disappeared, to the 1900s.



Hayeur Smith set out to test Østergård's hypothesis against the archaeology, starting with the evidence from Tatsipataa. McGovern's specimens turned out to be "phenomenal," she says. Excavated under controlled conditions from a well-documented series of layers of remains, they were brimming with information about changes in weaving, when these changes occurred—and, quite possibly, *why.* Collaborating with McGovern's doctoral student Konrad Smiarowski, Hayeur Smith reviewed their excavation plan, a depiction of how the artifact layers were deposited over time. It indicated that the weft-dominant cloth appeared somewhat later in time.

By dating the Tatsipataa cloth remains, Hayeur Smith was able to correlate the ratio of weft to warp threads in each sample with published records of climate data. As Østergård had hypothesized, weft-dominant cloth did indeed increase as temperatures dipped in the 1300s. "It matched up perfectly with the climate data!" she says.

Still, as exciting as that finding was, "it was just one site," Hayeur Smith says. To prove that women were adapting their weaving to climate change, she had to collect remains from all over Greenland during different time periods.

In September 2014 Hayeur Smith's pursuit of women in textiles brought her to what had once been an old trading house on Greenland's Nuuk Harbor, where she could watch icebergs float by. Built by 18th-century Danish-Norwegian missionary Hans Egede, the building was now used by the Greenland National Museum and Archives to host research teams. But she was the only researcher there. At night the storms battering the house and the groaning beams evoked a sense of uneasiness that challenged her scientific outlook. Later she would learn from locals that this abode, situated beside a graveyard for smallpox victims, was widely regarded as haunted.

She laughs at her fears as she recounts them in 2022 from her cozy home office in Pawtucket, R.I., which is filled with artwork and portraits of her French Canadian and American great-grandfathers in antique oval frames. In the Nuuk museum and, during another trip that same year, in the National Museum of Denmark in Copenhagen, Hayeur Smith inspected some 700 cloth specimens from multiple archaeological sites across Greenland. She returned to Nuuk in 2017 to study even more samples. With all the dating she did, plus Østergård's, she was able to track the evolution of weft-dominant cloth and correlate it with the years of climate change. "I *confirmed* [it was] climate change," she says.

Flicking her long hair back from her face, Hayeur Smith points to a graph in her book. "Look, that's the climate data." She draws my attention to an arrow that goes down to the year 1320. "That's when you see

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weft-dominant cloth," she says. That type of cloth becomes widespread between 1300 and 1362.

After those dates, the weaving of weft-dominant textiles intensifies. Previously a minor type of cloth, "it becomes the most common textile produced in Greenland," she wrote in *The Valkyries' Loom*. It was "almost certainly" a response by local weavers in Greenland in this medieval era to cope with colder temperatures. Hayeur Smith had found her women. "I could see in the piece of cloth," she says, her voice buzzing with excitement, "the actual deliberate decision-making that women were doing, like *it's getting cold; let's change the way we weave our cloth*. It's almost unheard of that you get to see people's direct actions and thought processes" so far in the past.

POWER SHIFTS

EVENTUALLY, THOUGH, NATURAL, political and economic forces combined to strip Icelandic and Greenlandic women of the power they possessed as a result of making the all-important cloth. By around 1450 the Little Ice Age, among other factors, had destroyed the Greenland Norse colony, and plague and political upheaval had roiled the Kingdom of Norway.

In 1603 Danish authorities under King Christian IV imposed a royal monopoly on trading and strictly required all imports and exports to go through Denmark, reducing Iceland's freedom to trade. And although Iceland continued to use *vaðmál* as currency and export it until the late 17th century, fish had replaced the cloth as Iceland's primary export starting in the 14th century.

Imitating the English, whose male weaving guilds had produced fine cloths on foot-powered treadle looms since the 1300s, the Danes trained North Atlantic men to weave on these faster looms. They set up production workshops in locations around Iceland, including Reykjavik. They gave women spinning wheels, a much more efficient way to create yarn than the traditional spindle whorls used on the drop spindle. The Danes also encouraged women to knit—a skill they'd learned in the 1500s—responding to a market demand for knitted exports. In addition, they imported fabric from Denmark to Iceland. Women could buy it to make clothing, saving them the relentless labor of weaving. In taking these measures, the Danes essentially pushed women out of the mainstream of weaving.

Nevertheless, as Hayeur Smith found in the archaeological record, women continued to weave their homespun cloth on their farms. Fragments of the textile have surfaced at 17th- and 18th-century sites throughout Iceland, including its wealthiest ecclesiastical center, Skálholt. She believes people used it as a statement of national identity in the face of Danish rule and the new laws imposing a transformation of the women's 900-year-old tradition of textile production. "I see it as resistance," she says.

Yet the Danes—and the growth of industrialization—eventually prevailed. By the early 1800s, Hayeur Smith says, no one even knew how to weave on the old looms. And women were worse off for it. Once textiles could be made so much faster on machines than by hand, they came to be associated with things considered "frivolous or peripheral to our daily lives or of interest and important mainly to women as their primary consumers," she observes in *The Valkyries' Loom*. "It was in part the Industrial Revolution that sealed the fates of women as second-class citizens and ensured that Western society would become so vehemently patriarchal."

Hayeur Smith remains committed to the pursuit of the tales only cloth can tell. As the once dubious McGovern observes, "after her publications, nobody's going to look at textiles the same way again." SA

MICHÈLE HAYEUR SMITH examines archaeological deposits at Gilsbakki spanning 1,000 years—from the early 10th century to the early 20th century.

Francine Russo is a veteran journalist specializing in social sciences and relationships. She is author of *Love after 50: How to Find It, Enjoy It, and Keep It* (Simon and Schuster, 2021).

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Digital Repression of Dissent

The Putin regime has a portfolio of digital tools to control information and crack down on protests within the country

By Sophie Bushwick

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As Russia's invasion of Ukraine drags on, an information war is raging alongside the physical fighting. Russia's attempts to spread disinformation have not yet found great success in the West. Within the country, however, President Vladimir Putin's regime is controlling the narrative through censorship, state control of media and other forms of digital repression.

This term refers to practices that use digital tools to stamp out dissent through a combination of actions, both online and offline. Such practices are not limited to authoritarian governments. A review of 192 studies of digital repression, published in March 2022 in *Science Advances,* demonstrates that local police forces, corporations and even powerful individuals have attempted to exert digital control in a variety of ways. "We're trying to connect the study of digital repression to a very long-standing literature on more traditional forms of repression," says co-author Jennifer Earl, a professor of sociology at the University of Arizona. "Because, of course, it's not that governments or private actors started to repress with the advent of digital and social media—they had already been using lots of repressive tools." Scientific American spoke with Earl in March about the different forms that digital repression can take, how Russia is using a portfolio of such methods and whether its attempts to construct an alternative reality will succeed.

[*An edited transcript of the interview follows.*]

What does the term "digital repression" mean?

In the paper, we talk about digital repression as two things: more physical controls and more information controls. You could think about those physical control measures as things that are being targeted at people because of their digital presences—such as the physical arrest of a blogger because of something that they had written—or using digital tools to more efficiently accomplish what are pretty long-standing [physical] repressive techniques, whether that's arrest, ongoing surveillance of a target, or infiltration and disruption of an organization. Repressors have been using surveillance for a really, really long time. It's just that digital tools change the scale and efficiency of that surveillance.

Then information controls are the use of digital tools to engage in repression. This is partly what you would think of as classic censorship: stopping people from getting information. This would include the use of Internet-based technologies for surveillance and larger-scale filtering of social media content. But in some ways, the architecture of social media and posts can make it difficult to fully control or censor information online. So governments and other repressors have started using what we refer to as "information channeling" techniques, where, in addition to trying to reduce the actual availability of content, you try to engage people in other content. For instance, as research in China has shown, you flood social media with pro-regime stories but also stories about local events that are entertainment-related and are cheerleading local government. Information channeling does also include misinformation and disinformation campaigns. You take those eyeballs, shift them from the content that you weren't able to censor completely and encourage people to focus on the much more available and prolific content that you would like them to see.

Both types of digital repression have been reported in Russia. In the "physical controls" category, there have been mass arrests of antiwar protesters and even reports of police in Moscow stopping people and forcing them to show their phone messages.

That's that first part of digital repression we talked about: the targeting of people for their digital presences. But a lot of the targeting is much more efficient and larger scale than asking people on the street to

Serg Myshkovsky/Getty Images (*preceding pages*)

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see their phone. Because a lot of governments, whether they have developed them in-house through their militaries or police or whether they have bought them from private contractors, have tools for monitoring Internet traffic—digital and social media posts. And so you certainly see many countries targeting people for physical repression—jailing, harassment, beatings and other kinds of things—based on what they have said or done online. But when we hear those stories about people checking phones on the street, to the extent that that has happened, that is likely more about its performative effect. One might imagine that's less about getting information that the Russian government couldn't get another way and more about the performance of that control to scare people, to more publicly telegraph, "Our eyes are on you. And just walking down the street, you're not safe if you have done certain things online."

In the second category, "information controls," independent media outlets in Russia are being forced to shut down, and social media platforms are being blocked. Does the country have a long history of this type of digital repression?

Many of the things that we can see right now going on in Russia are things that are not new to the Russian playbook. Part of some authoritarians' playbook is to try to control what people can get access to. So you have seen, in some places, restrictions on what kinds of platforms are accessible—or at least the rules under which those platforms can remain accessible. That's been a huge issue in China. Censoring media and then pushing out preferred stories through proregime media is a long-standing tactic in many authoritarian nations, including Russia. And we see that on a really high volume right now. So lots of Western journalists are not able to report right now because of fear of reprisals for that reporting. That's a real intensification of something that was already happening.

What we often see with repression, including digital repression, is that governments and other actors don't just do one thing. They really use a portfolio of techniques, particularly in major areas of concern for them. So it's really important for Putin right now to try to control this message. But in today's day and age, you don't just control it by arresting protesters on the street. You don't just control it by making it illegal to report on things that the Russian government doesn't want reported on. You also try to distract people and feed them false information so that they are paying attention to a reality that you, as a regime, have constructed.

There was some reporting where people who have been contacting relatives in Russia have found out that their relatives, to their great surprise, don't believe there is a war and that Russian soldiers would fire at civilians. They really believe that this is a limited special operation and that the Ukrainian government is run by Nazis. That set of beliefs is not something you conjure in a moment—it's a set of mistaken beliefs that Putin and the Russian regime have been working on for a while. What we're seeing are not things that have not happened before, [but they are] in full bloom right now. And that means that people are all of a sudden seeing, in very vivid detail, what repressors can accomplish with disinformation campaigns.

What is one of the things you have learned about these techniques from studying nearly 200 studies on digital repression?

There has been a considerable amount of concern that digital and social media technologies help people who would suppress dissent more than they help protesters. Although it is true that state and private actors—as we show in the paper through our literature review—have amassed and used a wide variety of surveillance and other forms of repressive tools, it is also the case that they don't always work. The results of repression are a gamble for state and private actors. I'm in no way defending, apologizing for or limiting the real impact those repressive tools have on individual people's lives. But efforts by repressors actually backfire plenty of times and increase protest, as opposed to decreasing it.

The results of repression are a gamble for state and private actors. Efforts by repressors actually backfire plenty of times and increase protest, as opposed to decreasing it.

Is it possible to predict whether Russia's increase in digital repression will succeed or backfire?

It is impossible to have a clear crystal ball about how this will play out. There are a few things, though, that are a little clearer. Despite heavy initial physical repression of protesters, mass arrests, heavy censorship of media and a very significant disinformation campaign, some Russians still are opposing the regime's actions. How many Russians will be able to continue doing that for how long? I think that is the real question that can't be answered in that crystal ball. But even this high-intensity level of repression, using lots of different forms of repression, has not been able to fully silence the Russian people.

Sophie Bushwick is an associate editor covering technology at *Scientific American.*

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Long Haulers and Chronic Illnesses

Millions of Americans have long COVID—and we are not prepared to manage the crisis

By Meghan O'Rourke

WHEN THE FIRST WAVE OF CORONAVIRUS INFECTIONS hit the U.S. in March 2020, what kept me up at night was not only the tragedy of the acute crisis but also the idea that we might soon be facing a second crisis—a pandemic of chronic illness triggered by the virus. I had just finished reporting and writing a book about infection-associated syndromes and contested chronic illnesses, long an underresearched and dismissed area of medicine. Medical science has increasingly understood that infections can trigger ongoing physical symptoms in a subset of people, yet the medical establishment has typically ignored the experiences of those people. Such conditions include myalgic encephalomyelitis/chronic fatigue syndrome (ME/CFS), so-called chronic Lyme disease, and more.

Sure enough, later that spring a cohort of patients who had caught the coronavirus in March began reporting that they were still not better. In online message boards, patients began sharing stories of what they called long COVID. Groups of "long haulers" banded together to call for more attention and research into their plight.

The clamor, combined with the scope of the problem, had a clear impact on medical attitudes, making long COVID visible in ways that ME/CFS had struggled for decades to become. In a matter of months centers dedicated to treating long COVID sprang up at respected research hospitals, such as the Center for Post-COVID Care at Mount Sinai in New York City. In itself, this is a hopeful development: when I got sick with a similar condition a decade ago, I longed for such a place.

The effects on research, too, have been dramatic, with scientists at numerous academic medical centers working to understand what long COVID is, how to measure it, and how best to treat or manage it. Akiko Iwasaki, an immunologist and head of a laboratory at the Yale School of Medicine, is one of them. "I used to focus mainly on acute infectious diseases, but with long COVID on the rise, a big chunk of my lab now focuses on long COVID and other postacute infection syndromes," she says. David Putrino, director of rehabilitation innovation for the Mount Sinai Health System, says he has seen "a sharp increase in interested researchers," in part because funding agencies such as the National Institutes of Health "have begun allocating increased resources to long COVID."

Three years into the pandemic, long COVID remains one of the biggest threats it poses. Early estimates suggested anywhere from 10 to 50 percent of unvaccinated people infected with the virus develop long-term symptoms. Vaccines may reduce the risk by as much as 50 percent, but according to Putrino, they do not eliminate it.

Yet long COVID was rarely discussed in public health messaging during the Delta and Omicron waves; officials focused on acute severe disease and death and largely ignored the debilitating—and life-altering—long-term effects that the virus has on so many people. We've had even fewer conversations about the societal responsibilities we have toward a growing generation of sick people, many of whom are between the ages of 30 and 50.

This lack of concern is even more surprising considering that we still understand little about the condition, including what causes it. Some theories suggest that the virus triggers rampant inflammation or autoimmune disease, others that the virus itself may persist in tissues in the body. What we do know is that millions of people are seeking care for a staggering array of symptoms that include fatigue, brain fog, racing hearts, breathlessness, pain, and more. The task of treating all these patients is exposing some of medicine's enduring weaknesses.

Modern medicine is based on replicability. Since the advent of germ theory in the 19th century, the field has taken an "if you can't measure it, it doesn't exist" view, as Harvard University researcher Susan D. Block put it to me. Medicine has a long history of stigmatizing diseases it does not understand and cannot yet readily measure. Clinicians like to be able to treat diseases that resolve. When patients present with chronic conditions or an array of systemic symptoms that are hard to quantify, doctors do not have quick fixes to offer. These

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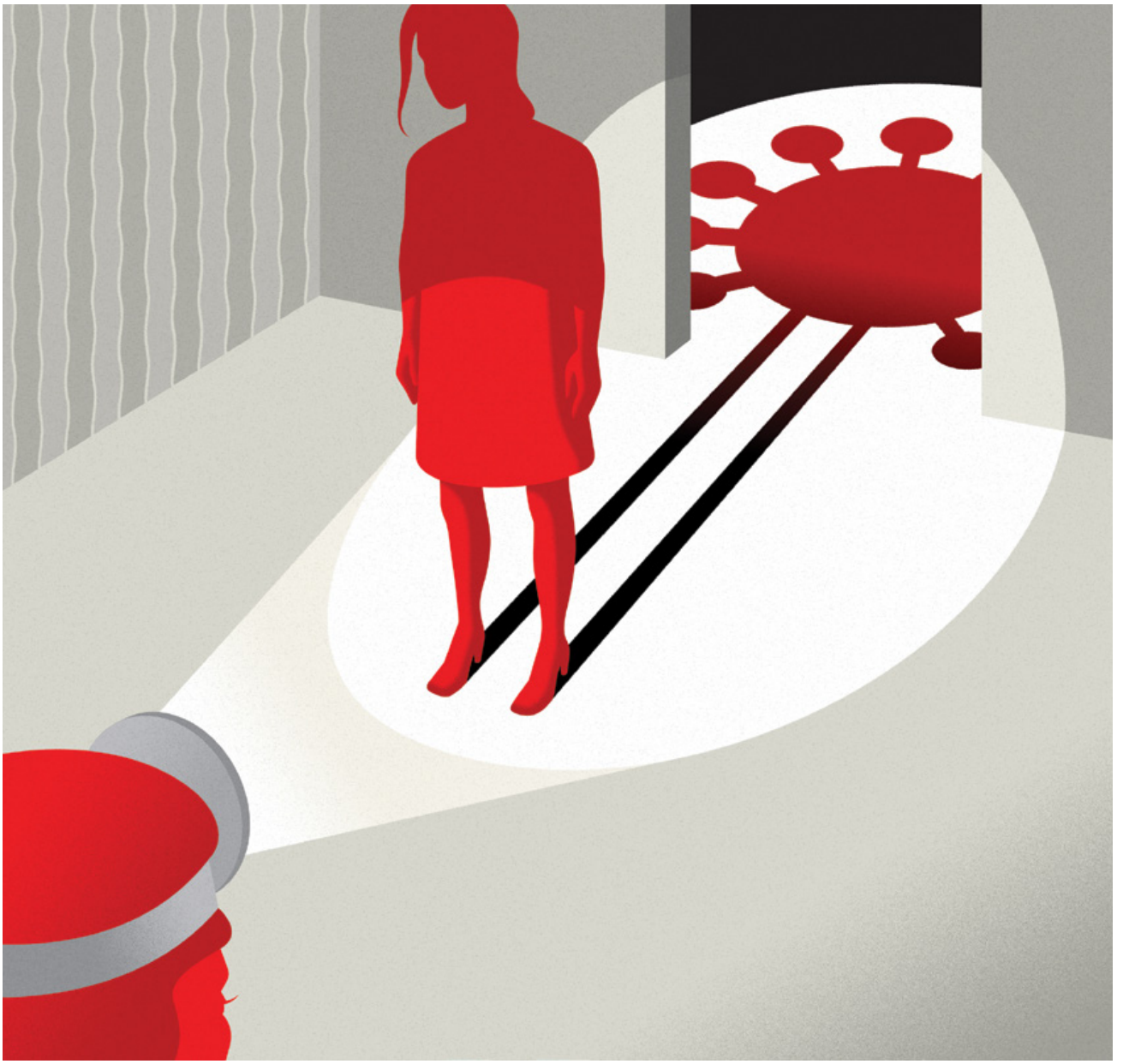

patients are often dismissed as malingerers or as suffering from a psychosomatic condition—and so it still is with long COVID.

Some patients have reported seeing doctors who want to help but lack the skills and bandwidth to do so. Early in the pandemic, staff at the Center for Post-COVID Care at Mount Sinai would spend hours with patients during their intake sessions. Compare that with the silo-based U.S. health-care system, which is designed to maximize efficiency: its basic building block is a 15-minute visit with a clinician. To treat long COVID effectively, then, Putrino thinks medicine needs more than just an infusion of interest and money. Additional funding, he says, will not "lead to a meaningful cultural change in the research and clinical world" until research centers start "actively involving people with these conditions" in the decision-making process.

The potential for transformation goes far beyond long COVID. Understanding what causes this condition might illuminate treatments for ME/CFS, tick-borne illness and other diseases that involve dysfunction of the immune system, many of which are on the rise. "I believe that understanding the pathogenesis of long COVID not only will help reveal parallel mechanisms for ME/CFS but also may hold a key to understanding autoimmune diseases, as many autoimmune diseases occur postinfection," Iwasaki says.

It is time for medical researchers to investigate these long-contested illnesses with the full force of science's power and for medical educators to train doctors in how to effectively *care* for chronically ill patients. If they do not, they will be failing not only this generation of patients but many millions more to come. SA

Meghan O'Rourke is editor of the *Yale Review*. Her essays, criticism and poetry have appeared in the *Atlantic*, the *New Yorker* and many other publications. Her latest book is *The Invisible Kingdom: Reimagining Chronic Illness* (Riverhead Books, 2022).

Illustration by Thomas Fuchs

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AMERICA'S MILITIAS

For some members, longing for a fictional "simpler" national past can transform into violence and hatred

By Amy Cooter

Illustrations by Mark Smith

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"IS THIS FIELD DAY?" I ASKED THROUGH MY CAR WINDOW ON A CHILLY, RAINY APRIL morning in central Michigan in 2008. A lone man dressed in head-to-toe camouflage, whose hand was casually resting on an AK-47 rifle strapped across his chest, nodded and stepped aside on the narrow road. I drove ahead to a parking area next to an old, red brick farmhouse and several acres of soybeans. About 50 people were gathering at a spot where the fields met a wooded bog. I was outside the village of Bancroft, at what was indeed the Michigan Militia's annual Field Day event. The group described it as a family and public outreach opportunity, held on private land that was owned by a World War II veteran.

Wood smoke drifted through the air from a campfire; some members were already loudly joking about the unpleasantness of the weathered, tarp-covered outhouse at the site, good-naturedly bemoaning the decision to not rent portable toilets as they had done the year before. A few of the men were already tearing open MREs—meals ready to eat that are packaged, high-calorie food typically issued to soldiers but also available at military surplus stores and on eBay.

Almost all the men were wearing some degree of camouflage and were laughing as they showed off new firearms, tactical vests or other equipment and told stories about past training events. The comparatively few women and children in attendance were more subdued and usually dressed in casual clothes rather than camo. Still, most of them participated in target shooting and other activities of the day.

This was the third militia event I had attended. I am a sociologist, and at that time I was a graduate student at the University of Michigan just beginning in-depth fieldwork and interview research about the militia movement in the U.S. I had approached members of this group a month earlier during a public meeting at a strip mall diner because I wanted to understand why people join civilian groups that prepare for armed combat, and I planned to examine whether militias propagate racism and violence. My fieldwork in Michigan, as well as in-depth interviews that included groups in other states, continued through 2013. Since then, I have maintained regular contact with militia members, especially in Michigan, and they update me with their activities and responses to political and social events. We regularly speak about their values and their motivations. I follow their online posts. In the summer of 2020 I conducted a survey asking members what they thought about protests related to COVID social restrictions and George Floyd's murder in Minnesota.

I have learned that there is important variation across militia groups. They fall on a spectrum. At one end are units whose activities are largely limited to outings for "grown-up Boy Scouts," as several members described themselves at the Field Day event I went to years ago. At the other end are units that are openly angry, whose members plot violence against government officials and advocate overt white supremacy. Some of the latter stormed the U.S. Capitol on January 6, 2021. The more extremist militia bands tote guns in public, wear military garb and endorse various conspiracy fantasies. They have confronted racial justice activists and protested pandemic public health measures in many states. In Michigan, people in one militia splinter group were arrested in 2020 and charged with plotting to kidnap Governor Gretchen Whitmer in retaliation for a perceived failure to uphold individual liberties.

Across this spectrum, however, militia groups share certain similarities. Their members are almost exclusively white men, and they espouse values of nationalism as well as yearnings to restore "better times" from this country's past. I and other sociologists refer to them as nostalgic groups. Their values

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are often entwined with racist and sexist attitudes, in part because they deny or disregard the hostility directed at minority groups and women during that idealized history. A metaphor I like to use to explain the connection across these groups is that it is like having multiple trees on the same small plot of land. They are separate entities, but their roots grow in the same soil. Their branches intermingle when the wind blows just right, occasionally getting close enough so that you cannot tell where one tree stops and another begins.

That shared soil—this idealization of an imaginary past with greater freedom—creates a way for members and even some entire units to move across this spectrum. They can start off merely telling stories around a campfire but over time turn to conspiratorial thinking, open hostility or even violent action. I have observed an increase in extremism in recent years, with people who used to focus on camaraderie and preparedness at militia events now echoing claims that the insurrection at the Capitol was nothing more than a protest. Others repeatedly posted on social media about the need to personally "do something" about the supposedly stolen presidential election. Members making this shift were on edge in 2020, believing their core values of individualism and self-determination had been threatened by racial justice movements, the pandemic and efforts to control it and by what they claimed—falsely—was fraudulent voting.

Many of these people heard their fears reinforced through right-wing news media and Donald Trump's rhetoric about threats from immigrants and corrupt Democrats. The most apprehensive members possess stronger racist or xenophobic attitudes and are more prone to move toward the extreme end of the spectrum. They are susceptible to appeals from hate groups such as the Proud Boys or overt neo-Nazis, believing that despite differences they all share the overarching value of protecting what they see as America's foundation.

I GREW UP IN A CONSERVATIVE, rural, East Tennessee community where firearms for hunting, target practice and personal protection are part of the culture. As a child, I learned gun safety and basic marksmanship, witnessed my father shoot and kill a rabid coyote that was trying to eat my pet rabbit, and, when I was old enough to legally do so, obtained my concealed carry permit. My background gave me a greater familiarity with firearms and the people who use them than other social scientists who have studied militia groups exclusively via media reports or online message boards. Militia members invited me to private trainings and other events very early in my fieldwork and openly talked to me about their beliefs, values and motivations.

No one really knows how many civilian militia groups exist because they repeatedly form, splinter into separate units and dissolve, as members' interests wax and wane. Typical units have no more than 20 or so members who consistently attend events, but some have only two people, and others have more than 200. In addition to the heavy skew toward white males—at least 90 percent in most groups—most participants are in their late 20s or early 30s, although I have known of members as young as 18 and as old as 70. There are a few women who fully participate in militias, and because of their activity they tend to be well respected and rise to leadership roles. (Jessica Watkins, a leader of an Ohio militia who was arrested for her participation in the Capitol riot, is one example.) Still, most militia units have a culture suffused with casual misogyny.

People in militias believe it is their constitutional duty as good Americans to be heavily armed and prepared to defend themselves, their families and their country against threats ranging from natural disasters to foreign invasion. They join to practice and share skills related to target shooting, land navigation and general emergency preparedness. Many members first learned these skills in the military. One 27-year-old man, who had a regular job as a cus-

MILITIA MEMBERS were among those drawn to the Capitol insurrection on January 6, 2021.

Tayfun Coskun/Anadolu Agency via Getty Images

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tomer service representative, told me that his militia participation was about "serving the public, wanting to do [his] part for the community." He proposed ideas for his group such as organizing fundraisers to help people who had lost their jobs. Members like him saw their militia involvement as simply another form of neighborly support and a means to connect to other people with similar values.

These people look to the American Revolution as their ideal historical moment and view the Founding Fathers as nearly impeccable paragons whose perceived individualism, fearlessness and rebellion should be emulated today. A longtime leader of the Southeast Michigan Volunteer Militia told me in numerous conversations that contemporary militia membership is purely about following the standard set by the Founding Fathers to uphold the Constitution—a refrain frequently repeated by other members at public militia gatherings I attended. He told me, "Look, as a people, we really need to get back to our roots, and we need to be a little better armed, and we need to understand that, you know, that's how you secure your society and that's how you keep it free is by having armed citizens." He went on to say he was "really inspired" by the courage of militia founders. He said those people were "labeled as radicals and extremists [when] all they were doing is quoting the Constitution."

Militia members often told me they long for a "simpler time" when, they insist, individuals—especially men—took more responsibility for working and providing for their families and when the federal government was smaller and not a substitute for self-sufficiency the way they perceive it to be today.

In their vision of the past, members generally ignore the oppression of people from nonwhite backgrounds that is part of American history. Very few militia members I encountered were openly racist. Some units even made regular but unsuccessful attempts to recruit nonwhite members and included messages on their websites intended to convey inclusivity. This was the leading statement on the Southeast Michigan Volunteer Militia's site until they stopped maintaining it about five or six years ago: "Everyone is welcome, regardless of race, creed, color, religion or political affiliation, provided you do not wish to bring harm to our country or people. If you are a United States citizen (or have declared your intent to become such), who is capable of bearing arms, or supports the right to do so, then YOU ARE the MILITIA!"

In conversations, militia participants do not appear to be aware that racism is broader than the undisguised, legalized segregation of the past or the continued hatred from open white supremacists. Most have limited understanding of how systemic racism prevents equal economic attainment or equal access to quality health care or educational opportunities.

For example, one member, a 56-year-old white man, a lifelong Detroit resident who worked in IT, blamed what he described as the "downfall" of his city on "forced busing" that happened in the wake of the Civil Rights Movement and was intended to help equalize school opportunity. Opposition to busing has a history of open racism, but this man was trying to make a different argument. He said he believed both Black and white families resented the busing policy, which required children to go to school far away from home and spend a lengthy time in transit. He said dislike of the policy made Black and white "good workers" abandon the city, leaving behind comparatively lazy workers and disengaged citizens of both racial groups.

He showed little comprehension of why his argument did not apply to Black families who cannot pick up and move elsewhere for a variety of reasons, including financial barriers such as lower home values, caused by long-standing discrimination in lending and real estate markets. The depressed prices prevent them from selling a house and then buying one in a better school district. Nor did this militia member understand that Black families might have embraced busing rather than resenting it: it was an opportunity to send their children to superior schools in a city that had historically neglected them.

Members of militias, in my analysis, show what sociologists call "modern racism," where they endorse ideas of cultural inferiority rather than biological deficiency. In one of the more conspicuous examples I encountered, an interviewee told me he was not "outright" racist and that he had good Black friends before going on to say that some Black people made him uncomfortable. "I guess when you see a group of them [young Black men] dressed up or somethin' and they're hippin' and hoppin' at a corner.… It's just that … I don't know, I guess it's just because I don't know them." His comment reflects stereotypical notions that treat groups of Black men as "otherized"—as different from his friendly group and as vaguely threatening, even though he did recognize that his lack of personal connection to them might be a factor in his negative perceptions.

Whiteness and masculinity are central features—though often not clearly obvious ones—in the rearview nationalism of militia members' values. Their nostalgic stories hinge on archetypes of independent, brave men whose heroic efforts were responsible for establishing a nation as these groups wish it to be again. Those men are always white. Groups vary in the extent to which they understand and embrace the race- and gender-biased elements of this narrative. Sociologist Ruth Braunstein of the University of Connecticut noted in a 2021 article examining the intersections of religion, race and nationalism that nostalgic groups take advantage of a "cultural power of whiteness" and "thus write themselves into their American story as the patriotic heroes who will

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alter the course of the country's decline by urging a return to the conditions of the past."

Historian Robert Churchill of the University of Hartford has developed a two-part typology that distinguishes between "constitutionalist" and "millenarian" militias and that has been invaluable for understanding how this kind of aggressive and selective nostalgia enables people to move to more extreme and violent groups. Constitutionalist groups, Churchill says, believe it is their personal responsibility to uphold an originalist interpretation of the Constitution focused on a heavily limited government. They see themselves as law-abiding patriots whose presence limits the overreaching actions of central authorities.

I found this in my research as well. One constitutionalist group leader told me he believed that public demonstrations by militia units "remind the government that they serve the people and not the other way around"; he indicated that he believes militia units visibly exercising their Second Amendment rights to carry weapons keeps the U.S. government from moving toward tyranny.

Millenarian militias, in contrast, take an offensive stance against governments and are generally more open to violent action. Their focus during meetings is less on self-sufficiency and bonding while target shooting. They spend more time on conspiratorial speculations about ways the government must be interfering in their lives and fantasize about exacting retribution for those actions.

For example, one millenarian member told me that his reason for militia membership was "revenge." He was a Desert Storm veteran who believed that the war in Iraq had been conducted under false pretenses and that the U.S. government had experimented on him and his fellow soldiers. He claimed this experimentation led to others in his unit dying early from cancer and other diseases and having children with high rates of birth defects. He said he had chosen not to have children of his own because he feared that outcome. His fear and bitterness led him to believe the government might persecute him for talking about his experiences, and he emphasized that he welcomed the fight. Although precise motivations for hating the government varied, this general attitude of anticipating and even yearning for a violent confrontation was common in millenarian members I encountered. About a year and a half after I interviewed this man, several members of his militia, which called themselves the Hutaree, were arrested and charged with crimes related to an alleged plot to kill Michigan police officers.

IN BOTH MY AND CHURCHILL'S estimations, for most of the early 2000s militias in the U.S. were about 90 percent constitutionalist groups and 10 percent millenarian groups, and most posed little threat of violence. But that proportion has shifted toward extremism in the past decade, we both believe, as members feel increasingly fearful of changing social conditions in a variety of areas—immigration, the pandemic, protests against police shootings of Black people and the presidential election—fears which Trump directly stoked.

Churchill says it "seems the millenarian wing has come to the fore." Even though the exact millenarian percentage in the movement is difficult to judge, his observation resonates with what I have seen. Constitutionalist groups that previously ridiculed conspiracy fantasies have pivoted to saying things like they were "monitoring" or "researching" claims from the far-right conspiracy movement QAnon, even as they denied fully embracing them. They share posts that prophesized terrorist attacks that never came to be. They pass around fake news stories about people in the antifa (antifascist) movement traveling on buses to locations all over the country and setting fires to stoke general chaos. One of the most common forays into conspiracy fantasies that I saw militias across the country post to social media pages leading up to the 2020 election were images of Joe Biden being affectionate with his granddaughter or other children. These were presented as purported "proof" of QAnon theories about pedophilia in Democratic leadership.

In 2020 some militias became more willing to bump shoulders with fundamentally racist groups in an effort to maintain their vision of America.

During racial justice protests and the stress of the pandemic in 2020, some militias became more willing to figuratively and literally bump shoulders with fundamentally racist nostalgic groups in an effort to maintain their vision of America. They stood together in public. I watched militia members discuss online some shared interests with previously adversarial groups. A member of an Indiana unit advocated in his social media posts for "loyal Americans" to work together to "take back" a civil rights protest zone in Seattle that had declared autonomy from the city. He believed stories that anarchists were planning to take over other American cities if such zones were left unchallenged. Some members who responded to my 2020 survey felt that COVID-related restrictions represented unacceptable state control. A few had similar objections to state power when police broke up social justice demonstrations,

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but many believed such protests were really being orchestrated by antifa and needed to be opposed.

Recently I have observed some constitutionalist members embracing such fear-driven ideas and rapidly drifting into the millenarian framework or even beyond, while sometimes taking other members with them. There was a disturbing example of this dangerous transition when some members of the large, public Michigan Liberty Militia splintered off to form a group called the Wolverine Watchmen. Then they recruited other people who had not previously been affiliated with the Liberty group. In spring 2020, according to court documents, the Watchmen plotted a coup of the Michigan governorship, angered by state restrictions on activities enacted to reduce the spread of COVID. Militia members said such orders were a red-line infringement on civil liberties. It appears that the group formed and radicalized after discovering that the Liberty Militia was not violent enough for its goals. [*Editor's Note: Five men were convicted in 2022 for their involvement in the plot to kidnap Michigan's governor Gretchen Whitmer.*]

This case is similar to another that received much less national attention. Shortly before the 2016 election, three militia members were accused (and ultimately convicted) of plotting to bomb a Somali refugee community. Lawyers for the accused men suggested that they had been moved beyond merely complaining about immigrants into planning actions to harm them because then candidate Trump's anti-immigrant rhetoric legitimized their fears about threats to America from Muslim outsiders.

The January 6 insurrectionists also seem to embody a movement toward extremism. Participants believed they needed to "Stop the Steal" and do something to prevent their preferred candidate and their vision of the nation from slipping away. The incursion was a mass act of violence and a clear escalation from the disgruntled chatter about supposed election fraud that many had observed during the prior several months. What is more, this was radicalization that extended beyond the boundaries of militia or other nostalgia groups. Many insurrectionists at the Capitol were previously unaffiliated.

Although federal law-enforcement attention has had a cooling effect, other people inspired by events at the Capitol may now seek out the more violent nostalgic groups for future action. Churchill told me that "there is convergence of apocalypticism, coming from the [militia] movement, and from QAnon, and from Evangelical Christianity. What we really saw on January 6 was not just the [militia] movement but a whole broader phenomenon."

To those of us who have studied militias for a long time, that phenomenon unfortunately has the feel of the 1990s, where nostalgic groups were more on edge, "less rational, a lot more emotional," as a long-term militia leader—a government employee—told me. Groups were ready to fight the state, and they feared the state was about to attack them after law-enforcement sieges in Waco, Tex., and Ruby Ridge, Idaho. The charged environment fostered men like Timothy McVeigh, who killed 168 people in a devastating act of domestic terrorism in Oklahoma City in 1995.

THERE ARE VERY FEW positive ways to look on the most recent developments. Perhaps one is that our country in general seems to have a greater awareness of the need to take militias and other nostalgic groups seriously. The House Committee on Veterans Affairs asked me and other experts to testify in October 2021 about extremist groups recruiting military veterans to their ranks. Various nostalgic bands have openly sought to recruit veterans for decades in part because they represent a commitment to the nation that can attract other new recruits. Extremist factions may also desire to use veterans' military skill sets for violent activities. Congressional investigations into these scenarios are long overdue, as is serious research into how veterans, especially those disenchanted with their service experiences, can be better supported and discouraged from radicalization.

Speculating on how militias may evolve in the future under increased scrutiny is difficult, in no small part because the units are still adapting to the aftermath of Trump's presidency. In contrast to what many members had predicted, they did not see President Biden enact martial law or start an immediate attack on Second Amendment rights. Millenarian militias and other groups on the extreme end of the nostalgic group spectrum nonetheless remain vigilant, and some are eager for violence. Members may be plotting deadly actions, but now they are on increasingly private and secure Internet platforms that are more difficult to monitor.

So the reality is that the danger has not abated. Quite the opposite: Militia emotions and activity could be easily exacerbated by another political leader who encourages exclusionary thinking and paranoia or by a foreign terrorist attack that nostalgic groups perceive as threatening to America's safety or culture.

Law enforcement must remain watchful for signs of radicalization in the movement, but as uncomfortable as it is, we as a society also must recognize that militias' violent potential is not limited to these groups. They are not fluke outliers. Members share ideological similarities with other white Americans who distrust the government and believe the country has declined because of increasing liberalism. Much work remains to repair the distrust and to protect innocent people from the violence that it breeds. SA

Amy Cooter is a senior lecturer in sociology at Vanderbilt University who has been studying militias and extremist groups for 16 years. Her analysis of neo-Nazis was published in *Sociological Inquiry* in 2006. She has testified before the U.S. Congress about her fieldwork in militia movements and how hate groups attempt to recruit military veterans.

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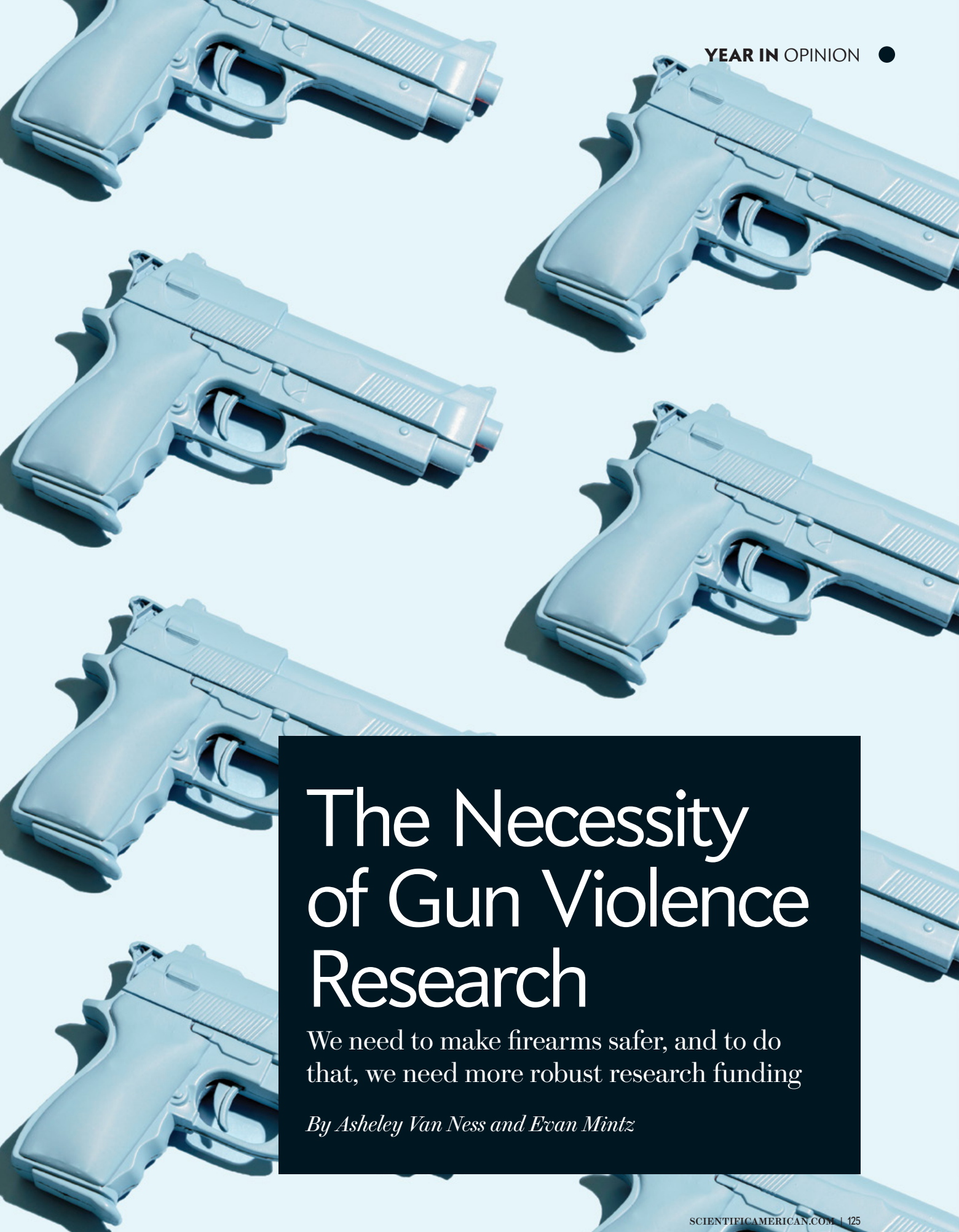

The Necessity of Gun Violence Research

We need to make firearms safer, and to do that, we need more robust research funding

By Asheley Van Ness and Evan Mintz

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THE U.S. SUPREME COURT'S JUNE 2022 DECISION IN *NEW YORK State Rifle & Pistol Association Inc. v. Bruen* represents the latest shattering of once routine norms around gun safety laws in the U.S. In this case, a 6–3 majority concluded that New York State's requirement for a license to carry a concealed handgun violated the constitutional right to bear arms, which the jurists believe is guaranteed by the Second Amendment.

New York's regulatory system required applicants to show "proper cause"—a specific reason—to carry a concealed gun. Six other jurisdictions (California, Hawaii, Maryland, Massachusetts, New Jersey, and Washington, D.C.), encompassing a population of 80 million people, have similar regulations. This decision casts grave doubt on all those laws, as well as on other rules where a future court might conclude that a policy is not consistent with a historical tradition of regulation. State legislators now face the challenge of passing regulations that comport with the Supreme Court's newly crafted approach to rules.

With multiple mass shootings within just weeks of the ruling, everyone knows what's at stake. The few statistics we have are stunning. Gun deaths are hitting record levels, whether by homicide, suicide or accident. More than 45,000 people died from firearm injuries in 2020. Firearms have also become the leading cause of death for children. These deaths come amid a surge in the domestic sale of firearms. The most recent Small Arms Survey estimates there are nearly 400 million guns in the U.S. That international study predates a surge of nine million firearms purchased during the first five months of the COVID pandemic—85 percent higher than expected.

Despite these mounting deaths, partisan deadlock often stands in the way of passing gun legislation, and opponents of new laws often point to a lack of evidence that proposed policies would reduce the harm caused by gunfire. The most effective tool to overcome such assertions would be objective research—if we had more of it. Unfortunately, there is not enough rigorous evidence about the best ways to reduce gun violence.

This is by design.

For more than 20 years the federal government failed to properly support research into gun violence. We spent about $63 in research dollars per life lost to gun violence, compared with roughly $1,000 per life lost to car crashes and nearly $7,000 per life researching sepsis, a life-threatening response to infection.

Two decades without these critical investments have left us with myriad open questions about the effects of gun policies. This gap in funding originated with the Dickey Amendment, which was imposed in 1996 to prevent the Centers for Disease Control and Prevention from advocating or promoting gun control. That rule was treated as a prohibition on all gun violence research. Although Congress clarified the law in 2018 to allow for research funding, there remains a vast gap where data were never collected. We have limited rigorous evidence about the issues discussed in the Bruen case, such as gun licensing, concealed carry and permitless carry. We even lack basic data on issues as fundamental as the number of nonfatal gun injuries in each state.

Trying to reduce gun deaths without this information is like trying to decrease freeway deaths without having any information on the number of car crashes or research on the effects of seat belts.

Fortunately, universities and private philanthropies, such as our organization, Arnold Ventures, have stepped up to try to fill the research gap. The nonpar-

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tisan National Collaborative on Gun Violence Research, which was launched in 2018 with support from Arnold Ventures and other funders, has awarded more than $21 million for more than 44 research projects on topics ranging from intimate partner violence to suicides to self-defense. But even this is a drop in the bucket for a public health problem so pervasive and unrelenting in its death toll.

A 2021 report by Health Management Associates, supported by Arnold Ventures and the Joyce Foundation, found that it would cost approximately $600 million over five years to conduct the most critical pieces of research and build out the necessary data infrastructure to collect accurate information on deaths and injuries caused by firearms.

To put that sum in context, NASA is spending $600 million on a new space telescope to detect potentially dangerous asteroids. In other words: $600 million is a perfectly reasonable price tag for a better understanding of how we can prevent one of the leading causes of death in the U.S.

Most of the proposed funding—roughly $475 million—would be needed to answer the 100 critical gun research questions identified by a Joyce Foundation Expert Advisory Panel. The rest would support implementation of the NORC Expert Panel's recommendations for improving U.S. firearms data infrastructure at state and federal levels (NORC is a social research organization based at the University of Chicago). This includes steps such as supporting local compliance with the National Incident-Based Reporting System, tracking nonfatal gunshot injuries and improving the timeliness of available data.

As the body of evidence begins to build, the RAND Corporation's Gun Policy in America program, which is also supported by Arnold Ventures, is working to document the highest-quality research and determine what gun safety policies are most likely to save lives. So far the clearest results point to child-access prevention laws—which make it a crime to allow children to have unsupervised access to firearms—as the best way to reduce suicide and unintentional injuries, and they indicate that "stand your ground" laws increase violent crime. There is also evidence that background checks and prohibitions based on domestic violence may prevent violent crime, and waiting periods may reduce suicides and violent crime.

It is critical to note that the absence of high-quality evidence does not mean we should ignore basic logic. For example, even as we continue to research red flag laws, lawmakers should not hesitate to ensure that people suffering from suicidal ideation can't readily access a firearm. This is not only common sense but compassion.

As for the impact of the Bruen case, RAND has found limited evidence—at least one high-quality study and no contradictory findings—that licensing and permitting requirements lead to a decrease in suicides, as well as other evidence that concealed carry laws lead to an increase in violent crime. Data are hard to come by, and the evidence could be more extensive if we decided at the federal funding level that these questions are worth answering. Philanthropy and university funding alone can't answer these questions.

We're already seeing progress on the funding front. After clarifying the meaning of the Dickey Amendment, Congress allocated $50 million over the past two federal budgets to the CDC and the National Institutes of Health to further gun violence research. A bill that would install some firearm safety measures is also moving forward in Congress. It's an admirable start, but the absence of 20 years' worth of research into gun violence—and the public policy it might have led to—has left us without lifesaving answers at a time when we need them the most.

Scientists and researchers have a critical role to play in helping policy makers and the general public understand the task facing us when it comes to fighting the scourge of gun violence. While all too frequent mass shootings and the resulting political debates may dominate the headlines, the reality is that our fundamental understanding of gun violence fails to meet the moment. Guns can be safer, and once and for all, we need to rebut the engineered idea that they can't be, or that they shouldn't be, with evidence.

$600 million is a perfectly reasonable price tag for a better understanding of how we can prevent one of the leading causes of death in the U.S.

We hear about the people who suffer from gun violence and the politicians charged with setting things right, but there is another story that needs to be told, too. This is a story about how data, research and evidence have been used throughout history to address critical matters of public health and save American lives. It is a story about how we can help stop gun violence. The Bruen decision leaves plenty of room for evidence-based gun regulations. No matter what the Supreme Court has ruled, a well-grounded scientific basis for gun policy is more important than ever—and only the federal government has resources at the scale needed to meet the challenge. SA

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Evan Mintz is director of communications at Arnold Ventures. He previously served as deputy editor of the *Houston Chronicle* editorial board and was a finalist for the 2017 Pulitzer in editorial writing.

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A Chilling Effect

I am a future psychiatrist hoping to provide care to transgender people. But I fear new anti-trans laws will make it difficult to do so

By Ashley Andreou

EVERY YEAR MARCH 31 MARKS TRANSGENDER DAY OF Visibility, a day when we should be celebrating the accomplishments of people who are trans, honoring their resilience and advocating loudly for their rights. Yet the growing onslaught of anti-trans legislation targeting the health-care decisions that families make with their doctors threatens to cast a shadow over this day.

In 2021 I lost a family member to the mental trauma of transgender discrimination, so I speak from a place of watching someone I love suffer from lack of support. These recent and proposed laws, none of which are grounded in evidence-based medicine, will affect the mental and physical health of adults and children and the families who support them.

I am in medical school, and I plan to specialize in psychiatry with the hope of working with people who are transgender or nonbinary. Instead of making me feel empowered to serve, the intent behind these laws makes me fearful for my future patients. The directive in Texas that calls gender-affirming health care "child abuse" makes me afraid to practice and outraged that any state can insert itself into the clinical decision-making that we spend thousands of hours honing over several years. There are so few doctors who treat people who are transgender, let alone specialize in the physical and mental medicine specific to their needs. These laws could dissuade clinicians from entering this line of work.

Instead of enacting laws that deny the basic health rights of the trans community—and signal to trans individuals that they are not safe, accepted or supported—policy makers, clinicians and advocates need to work together to create laws that counteract and prevent the health disparities that are exacerbated by the enduring discrimination against this community.

One of the biggest points of misinformation in the lobbying for these laws is what constitutes gender-affirming health care. Gender-affirming care is defined as treatments that either delay the onset of physical changes associated with puberty or create physiological and physical changes that affirm one's gender identity (for example, hormone therapy or surgery). It is important to note that transitioning is a spectrum—not everyone who is transgender chooses hormone therapy, and not everyone chooses surgery. Yet all options are at stake with some of the laws that have passed or been proposed.

Doctors do not offer gender-affirming therapy rashly, and they prescribe puberty blockers only after working with a younger transgender person considering transition for a long time. Access to puberty blockers is critical because puberty's effects on certain body parts cannot be easily reversed by hormone therapy later in life (for example, testosterone's effects on voice). Altogether, the process requires coordinated counseling and medical oversight from a multidisciplinary clinical team that can include psychiatrists, endocrinologists and urologists, among others.

About 25 percent of transgender and nonbinary people choose gender-affirming surgery. Medical guidelines do not recommend surgery (such as facial reconstruction, mastectomy or phalloplasty) until a person is 18 years old, a point purposefully misrepresented by politicians who falsely say doctors are operating on young children.

More than 58,000 transgender teenagers who are transitioning are at risk of losing access to their medical care, according to a report from the University of California, Los Angeles, School of Law's Williams Institute. The effects of these bills and laws would be devastating. A large survey published in *Pediatrics* in 2018 found that 30 to 50 percent of young trans and nonbinary people reported a previous suicide attempt, compared with less than 9 percent of all adolescents.

Experts hypothesize that this greater suicide risk among trans youth is linked to internalized rejection and shame. In contrast, transgender youth who are supported by their families and receive gender-affirming care have markedly lower rates of depression: gender-affirming care has been associated with a nearly 40 percent reduction in depression and in attempting suicide in the past year. Furthermore, trans youth who have access to puberty suppressants have a much lower risk of lifetime suicide as adults.

As Texas's legislature debated anti-trans bills in 2021, the Trevor Project, an organization focused on LGBTQIA+ youth suicide prevention, received more than 10,800 total crisis contacts. Transgender or nonbinary youth made up more than 3,900 of those crisis contacts, and many of them reported feeling stressed, turning to self-harm and considering suicide as a result of the anti-LGBTQIA+ laws proposed by politicians in their state. Between 2020 and 2021, the Trevor Project recorded a 150 percent increase in LGBTQIA+ youth

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TRANSGENDER RIGHTS advocates hold pride flags during a rally against Ohio legislation banning trans women from female sports in June 2021 in Columbus, Ohio.

in Texas contacting the organization in crisis and seeking support. As a future psychiatrist, I find it incomprehensible that state lawmakers would willfully harm the mental health of so many young people.

All this legislation is at direct odds with the medical guidance of the American Psychiatric Association, the American Medical Association (AMA) and the American Academy of Pediatrics (AAP). These medical organizations recommend these medications and procedures for transgender individuals because there is a corpus of scientific literature affirming their benefits when medically indicated. These treatments are far from new and untested: puberty blockers have been used in medical care since the 1990s.

Calling me a child abuser will not stop my future patients from seeking care. Similar to the effects of efforts to stop abortion, transgender people and their families are liable to turn to unregulated black market products outside the purview of the Food and Drug Administration's monitoring of hormone product safety and quality. I can't fulfill the Hippocratic oath knowing that my inability to provide gender-affirming care might force patients into unsafe situations.

Numerous bills also propose criminalizing physicians if they offer transgender hormone therapy. In medical school, we had lectures on the importance of providing gender-affirming care, as well as panels specifically on the health-care experiences of transgender patients.

The closure in 2021 of Texas's only multidisciplinary clinic for transgender youth, GENECIS, in response to pressure from the governor is evidence of the stifling effect these laws have already had on medical professionals. [*Editor's Note: A court order allowed GENECIS to start taking patients again in May 2022, pending any appeals.*]

As highlighted by the pandemic, a dangerous risk factor for burnout among physicians is when they cannot control the health outcomes of their patients. Yet these bills go one step further, creating preventable negative health outcomes, and would introduce a new level of powerlessness and morale loss among providers. The AMA and AAP have both issued statements opposing recent anti-trans bills.

When speaking out against an anti-trans bill in Arkansas in 2021, Michele Hutchinson, a pediatrician at Arkansas Children's Hospital, said, "I guarantee you, if this bill passes, children will die. And I will call you guys every single time one does." In April 2021 that bill passed.

The day when police came to my house to tell my family that my uncle was found dead from an overdose after years of struggling with her identity, I felt like I was living through a nightmare.

In the painful days after, I committed myself to partnering with transgender communities to provide medical care and advocacy. Yet as legislators continue to signal that they would rather see people like my uncle dead than happy, alive and thriving, my grief has not subsided. Reading Texas Governor Greg Abbott's letter declaring gender-affirmative care "child abuse" and understanding that a growing number of legislators seek to bar me and other physicians from providing lifesaving care, I know my family's nightmare hasn't ended.

Despite these legal battles underscoring the transgender community's perseverance in the face of harrowing challenges, suffering is not what Transgender Day of Visibility is about. Unfortunately, brazen and medically uninformed politicians denying basic human rights over binary ideas of gender have left us no choice but to rally and continue to fight. My uncle, who was a transgender woman but liked being called "uncle," deserved more in life. This is what I can do for her in death. SA

Ashley Andreou is a medical student at Georgetown University.

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Get Ready for the Next One

Contagions worse than COVID will prevail if neglect of global public health continues *By the Editors*

AFTER OMICRON COMES *pi* in the Greek alphabet. And then *rho, sigma, tau*.... Before SARS-CoV-2 finishes its grand tour through the Greek alphabet, the global public health establishment should do what it should have done long before this coronavirus emerged. It must put in place the basic health systems needed to detect new outbreaks and deploy technologies that allow for vaccines and medicines to be manufactured and administered in low- and middle-income countries.

Because they have often refused to treat COVID as a common threat that demands a unified response, policy makers have yet to thwart the predations of a virus that, to channel the Greeks again, affects all (*pan*) people (*demos*). This myopia means that these mistakes could be repeated when a new pandemic arrives.

The next time could be worse. The National Academy of Medicine predicted in November 2021 that a flu epidemic akin to the one in 1918 and 1919 could prove more catastrophic than COVID-19. The preconditions for such a disaster are in place. A warming planet, megacities, mass migration, intercontinental travel and habitat loss are among the reasons that infectious diseases, like intensifying typhoons and hurricanes, have become part of our lives.

Fast-tracked development of diagnostics, vaccines, monoclonal antibodies and antiviral drugs marks an undisputed medical triumph of the COVID era. Also notable, however, is the failure of governments and international organizations to use our current predicament to rectify glaring public health deficiencies.

The Global Health Security Index for 2021 rated the world's 195 countries as "dangerously unprepared" to deal with future epidemic and pandemic threats. The average score for individual countries came in at 38.9 out of 100, about the same as the 2019 rating—before the pandemic began. Many countries failed to grasp that the pandemic presented an unparalleled opportunity to lay the groundwork for coping with not only this public health crisis but also future ones.

Readiness for a COVID-30 or a new pandemic flu strain—or, for that matter, an out-of-control bioweapon—will require new generations of surveillance tools, diagnostics and drugs, as well as, say, a "universal" coronavirus vaccine that can counter any strain. Having sufficient available vaccine formulations with long shelf lives would also help alleviate the inequities that have accompanied distribution of shots. Underscoring the absence of "global" in "global public health," Portugal had fully vaccinated 89 percent of its population by mid-January 2022 but Mali only 2.8 percent.

The most pressing priority should be a return to basics, both globally and locally. COVID has served as a painful demonstration that public health is as essential to national security as a standing army. And the cost of health security is minimal. In 2016 the Commission on a Global Health Risk Framework for the Future estimated that for 65 cents a year for every person on the planet, we could upgrade national pandemic preparedness programs worldwide. An investment of $4.5 billion—far less than the price of a single new ballistic missile submarine—might prevent the global loss of millions of lives and an economic hit in the trillions of dollars.

The basics entail not only building new systems to prepare for pandemics but a major strengthening of institutions already in place. Public health legal expert Lawrence O. Gostin has noted that the World Health Organization had a 2022–2023 budget of $6.12 billion, which is less than those of some major U.S. teaching hospitals. The WHO needs not just money but reforms that give it the authority to better monitor and intervene when new infectious diseases emerge. At the country level, the most basic of basics consists of functioning national systems that furnish medical care for all and financial help, as needed, for child care, food, housing and other measures to waylay the poverty-related chronic diseases capable of sending even a relatively young adult onto a ventilator during a future pandemic.

After repeated outbreaks of horrific diseases such as SARS, Ebola and Zika, perhaps this calamity will prove traumatic enough to bring about a coherent remake of the current system. Deaths from COVID worldwide by late October 2022 nearly equaled the population of Lebanon—and the pandemic is still with us. Only when global public health commands the attention of policy makers in the same way as a new contract for nuclear submarines will Greek letters return to their more familiar role in American life as naming conventions for student groups on college campuses. SA

Illustration by Martin Gee

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Evidence Shouldn't Be Optional

This U.S. Supreme Court often ignores science when handing down decisions, and it affects far too many lives *By the Editors*

DURING A TUMULTUOUS FEW WEEKS IN the summer of 2022, the Supreme Court ignored the scientific evidence underlying safe abortion, the need to slow climate change, and the value of gun safety laws. It is alarming that the justices are now set to consider a voting rights case in the current term, given Chief Justice John Roberts's feelings on what he calls the "sociological gobbledygook" of research into the effects of gerrymandering.

The promise of democracy is being sorely tested by judgments from the Supreme Court's conservative justices in cases involving health, welfare and the future of the planet. Over and over in the 2021–2022 term, their decisions put industry, religion (specifically, a conservative strain of Christianity) and special interests above facts. They have devalued the role of expertise.

Disregarding science and evidence is a terrible shift for the highest court in the land, which once safeguarded the health of the public in rulings that upheld state vaccine mandates and safe food production. This is in contrast to the way our current conservative justices have viewed COVID restrictions, whether exempting religious groups from bans on group gatherings or barring vaccine mandates for large businesses. Even in decisions that uphold basic public health tenets, conservative justices have spouted misleading scientific claims. In his dissent on the court's decision to not take on New York's vaccine mandate law for health-care workers, Justice Clarence Thomas laments that the workers demanding a religious exemption objected to available COVID vaccines "because they were developed using cell lines derived from aborted children," wording that obscures that the cells were grown in a lab based on elective abortions decades ago and also are used in the development of routine drugs.

This shift away from our social responsibilities for health and welfare is one that we fear will lead to needless suffering and death. We urge the court to change its reasoning—to value statistics, to value research and to understand how ignoring it in making decisions is contrary to common decency and their responsibility as jurists to the American people.

In their decision in *Dobbs v. Jackson Women's Health Organization,* the majority justices ignored what we and others have repeatedly reported: abortion is safe—much safer than pregnancy itself—and denying people access to legal abortions leads to poorer physical and mental health outcomes, not to mention economic outcomes. In overturning *Roe v. Wade* and shunting abortion rights to states, the justices who voted in favor of Dobbs put religion and the status of a mass of cells over the health and welfare of actual people who make up approximately 50 percent of the U.S. population. They also indicated their disregard for the medical profession and the privacy of the doctor-patient relationship that the justices in the majority have no doubt continued to enjoy since their ruling became practice.

In striking down New York's gun safety law, the majority justices ignored data that show that unfettered access to guns leads to more murders and suicides and not fewer crimes. They ignored data showing that guns are now responsible for more child deaths than automobiles. They even ignored data that showed that once you repeal a gun law, gun-related killings go up. It was a cold-hearted decision, against the backdrop of Uvalde, Buffalo and every mass shooting our nation has suffered in the past decades. It was another slap in the face of our health-care system and the emergency clinicians who must try to save people shredded apart by high-powered weapons that are incredibly easy to get. As we have said before, gun safety laws are part of what makes a compassionate nation, and in this, the majority justices showed their callousness.

And then there is climate change. In stripping power from the EPA to help power plants mitigate their carbon output, the majority justices again said evidence doesn't matter, science doesn't matter. Our planet is warming. Coal is one of the largest contributors of greenhouse gases in the world. Taking regulatory power away from the EPA now puts states in charge of slowing climate change. Piecemeal efforts will not yield the reductions we need to slow warming. Federal action, as part of global efforts, is the necessary solution to this problem. And climate change is a public health issue. An increase in ferocious winter storms, unbearable heat, damaging rain and wildfires—these all affect the health and welfare of people in the U.S. The science is clear on this: we have to act now, and the Supreme Court has made those actions harder.

As with every level of government, there is no requirement that the Supreme Court factor science into its decision-making. And as Justice Amy Coney Barrett has said, "I'm certainly not a scientist." But expertise matters, and knowing when you don't know something and seeking that information makes for better justice. Yet in their efforts to be constitutional purists, at least when it suits their ideology, the justices in the majority show that ignoring science and evidence is their modus operandi. Instead they are using their power to uphold a certain vein of religion: last term the majority ruled against separation of church and state in two education cases, one of which forced Maine to fund schools that teach children misinformation about evolution and climate science.

The U.S. once inspired other countries to protect people's liberties. Now the rest of the world is watching and reacting to the decisions that our Supreme Court is making. And it's not good.

You don't need to be a scientist or mathematician to make good decisions and judgments. But if you are a justice of the U.S. Supreme Court, with the lives and livelihoods of hundreds of millions of people hanging on your every opinion, you owe it to us to use the data that science painstakingly compiles when handing down your decisions. We cannot go back to a world of religious and racial supremacy, where the bodies of women and people of color are objects without self-determination. We must not become the dystopian future so much science fiction has warned us about. Let evidence rule judgment. SA

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Generational Climate Change

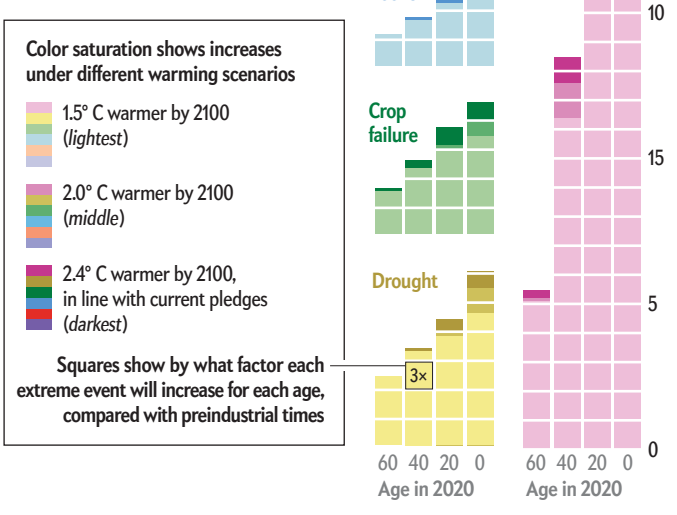
Young people will suffer the most from warming temperatures

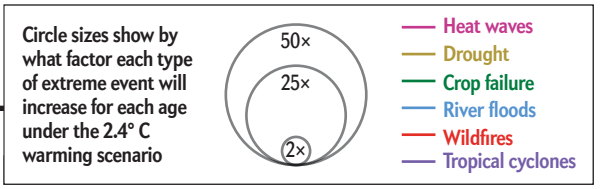
By Andrea Thompson | Graphic by Amanda Montañez

Babies born today will experience far more disruptions fueled by climate change than their parents or grandparents. In a study published in October 2021 in *Science,* Wim Thiery of Vrije Universiteit Brussel in Belgium and his colleagues combined climate model projections under three global warming scenarios with demography data to calculate the lifetime exposure to six types of extreme weather for every generation born between 1960 and 2020. Even as a climate scientist acutely aware of the dangers of rising temperatures, "seeing the numbers as a person, as a parent, is a punch in the stomach," he says. Young people in the Middle East and sub-Saharan Africa and those in low-income countries will see the largest increases in exposure. These estimates examine only changes in the frequency of extreme events—they do not represent how those events may become more intense and longer-lived. Although "young generations have the most to lose if global warming reaches higher levels," Thiery says, they also have the most to gain if greenhouse gas emissions can be reined in. "That is a key message of hope."

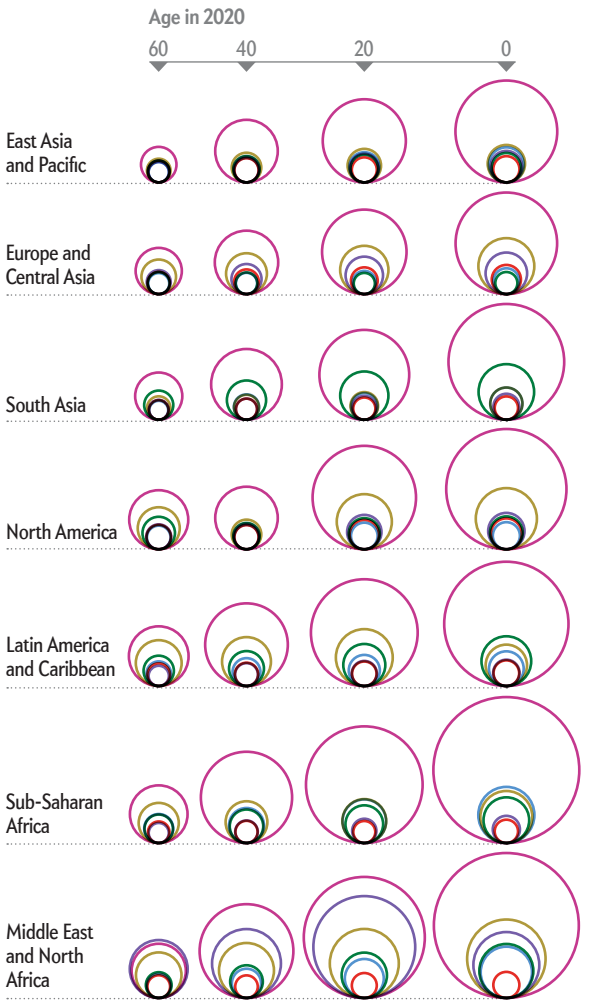
EXPOSURE TO EXTREME EVENTS BY AGE

It seems intuitive that younger generations will feel the effects of climate change more than older ones. But quantifying this phenomenon reveals just how stark the disparities are, particularly in terms of exposure to heat waves.

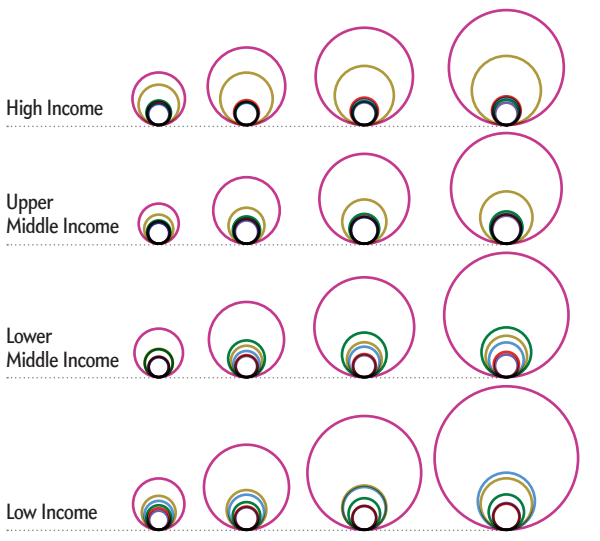




VARIATION BY WORLD REGION



VARIATION BY COUNTRY INCOME



Source: "Intergenerational Inequities in Exposure to Climate Extremes," by Wim Thiery et al., in *Science*, Vol. 374; October 8, 2021 (*data*)

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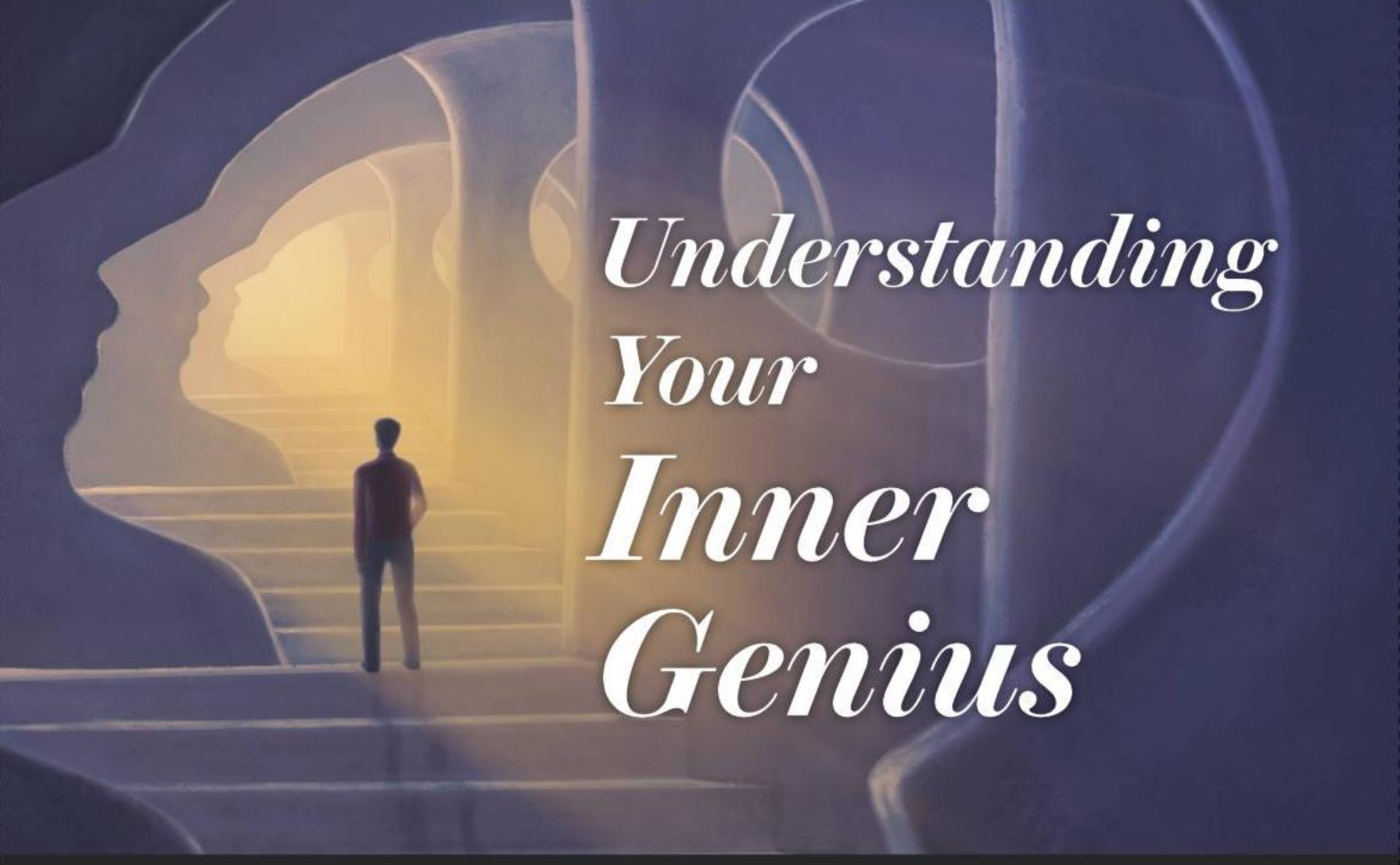

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